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METEOROLOGICAL FACTORS IN THE SUNDANCE FIRE RUN

Arnold I. Finklin

FOREST SERVICE
U S
DEPARTMENT OF AGRICULTURE

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah 84401

THE AUTHOR

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ABSTRACT

Strong, sustained, southwesterly winds were a major factor in the Sundance Fire run in northern Idaho during which the fire front raced 16 miles northeastward within a 9-hr. period on September 1, 1967. These winds were found to be dependent upon an unusually strong summertime pressure gradient ahead of an approaching trough, bringing windspeeds of 40 to 50 m.p.h. in the free atmosphere a few thousand feet above ground. Surface winds, though generally reduced by friction and varying according to local topography, were indicated at around 35 m.p.h. at exposed mountaintop or ridgetop locations in the fire area; gusts reached as high as 50 to 55 m.p.h. The strong airflow aloft was an atmospheric feature of large scale; its progress across the Pacific Northwest area could be tracked on weather charts, at least in retrospect.

This paper examines various other aspects of the weather situation, for example turbulence or subsidence, that may possibly have contributed to the strong surface wind (and the requisite low relative humidity). These included a dry cold front and an upper tropospheric jetstream; their importance, weighed, e.g., against the strong pressure gradient existing at all levels of the troposphere, appeared minor.

OXFORD: 111.0:43.
KEYWORDS: meteorology, fire (forest), wind, humidity.

INTRODUCTION

The importance of sustained strong winds in the phenomenal run of the Sundance Fire in northern Idaho, on September 1, 1967, was quite evident to persons at the scene. The fire, burning along a 4-mile active front, swept 16 miles northeastward in a 9-hr. period between 1400 and 2300 Pacific daylight time (P.d.t.). In the process, it burned more than 50,000 acres[1] of forest and claimed two human lives.

From the research standpoint, the Sundance Fire run was unique in the large amount of observational information obtainable within one afternoon and evening. Researchers themselves had been among the many persons already in the vicinity, drawn by adjacent project fires. An unusual opportunity was thus presented for a fire-case study, which was soon undertaken at the Northern Forest Fire Laboratory, Missoula, Montana. Resulting details of the Sundance Fire, its behavior, and analyses of the various factors such as fuels, topography, and weather have already been published (Anderson 1968).

The present paper portrays the associated weather, or meteorological, factors in greater detail. A more complete picture is thus available for use and comparison in future fire situations or studies. Our attention will naturally focus on the wind, and also on the humidity, which we will follow in relation to both the large-scale weather pattern and the fire behavior.

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[1]Combined Federal, State, and private land either in or adjoining Kaniksu National Forest.

BACKGROUND OF SUNDANCE FIRE

Location

The general location of the Sundance Fire is shown in figure 1. A more detailed portrayal of the burn area and immediate topography is given in figure 2. The burned forest was composed of mixed conifers [predominantly western larch (*Larix occidentalis* Nutt.), alpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and Engelmann spruce (*Picea engelmannii* Parry)] interspersed with logged areas. Fuel loading per acre varied greatly, from about 1 to 20 tons of combined crown material, brush, and ground litter.

The Pre-Run History

The designated Sundance Fire was actually one of five started by lightning on or near Sundance Mountain on August 11, 1967, 3 weeks prior to the major run. The four others were discovered, attacked, and put out by control forces within 1 to 9 days, after only a few acres had burned. The fateful fifth one was quiet and eluded discovery until August 23.

During the 3-week interim preceding the major fire run, the weather in the northern Idaho area was largely under the influence of an upper-air ridge, giving abnormally warm, dry, and rainless conditions. Winds were mostly light. Fire danger built steadily upward to the highest levels in a 14-year available record. The buildup index (National Fire-Danger Rating System) at Priest River Experimental Forest reached 248 on August 15 (equaling the high set in August 1959) and was up to 348 by September 1. This weather regime was temporarily interrupted by somewhat cooler and windier conditions during August 21-25 as two successive broad upper-air troughs moved through the area. It was during this period, on the evening of August 23, that the designated Sundance Fire first erupted and made its location known. This activity occurred on the west slope of Sundance Mountain and was apparently triggered by southwesterly winds that reached at least 20 to 25 m.p.h., gusting to 35 m.p.h., based on reports from neighboring mountaintop fire-weather stations. Weather maps showed the passage of a dry cold front ahead of the approaching upper trough. The fire was contained after burning 35 acres and was quiet for the next 5 days, during which time suppression activities continued.

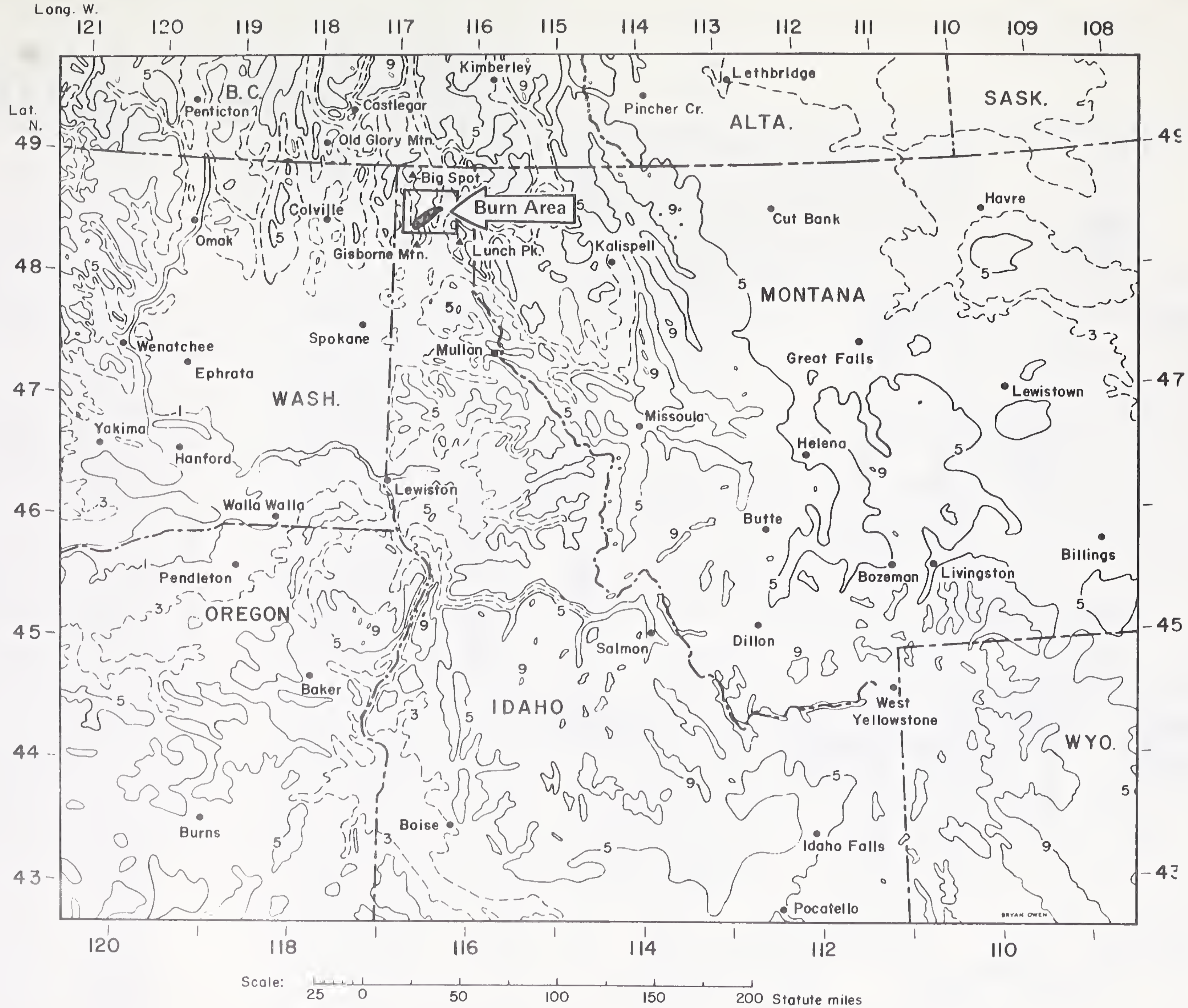

Figure 1.--Map of Northern Rocky Mountain area, showing general location of Sundance Fire in northern Idaho. Elevation contours are drawn at 1,000, 5,000, and 9,000 ft. m.s.l. (solid lines); also at 3,000 ft. (dashed line).

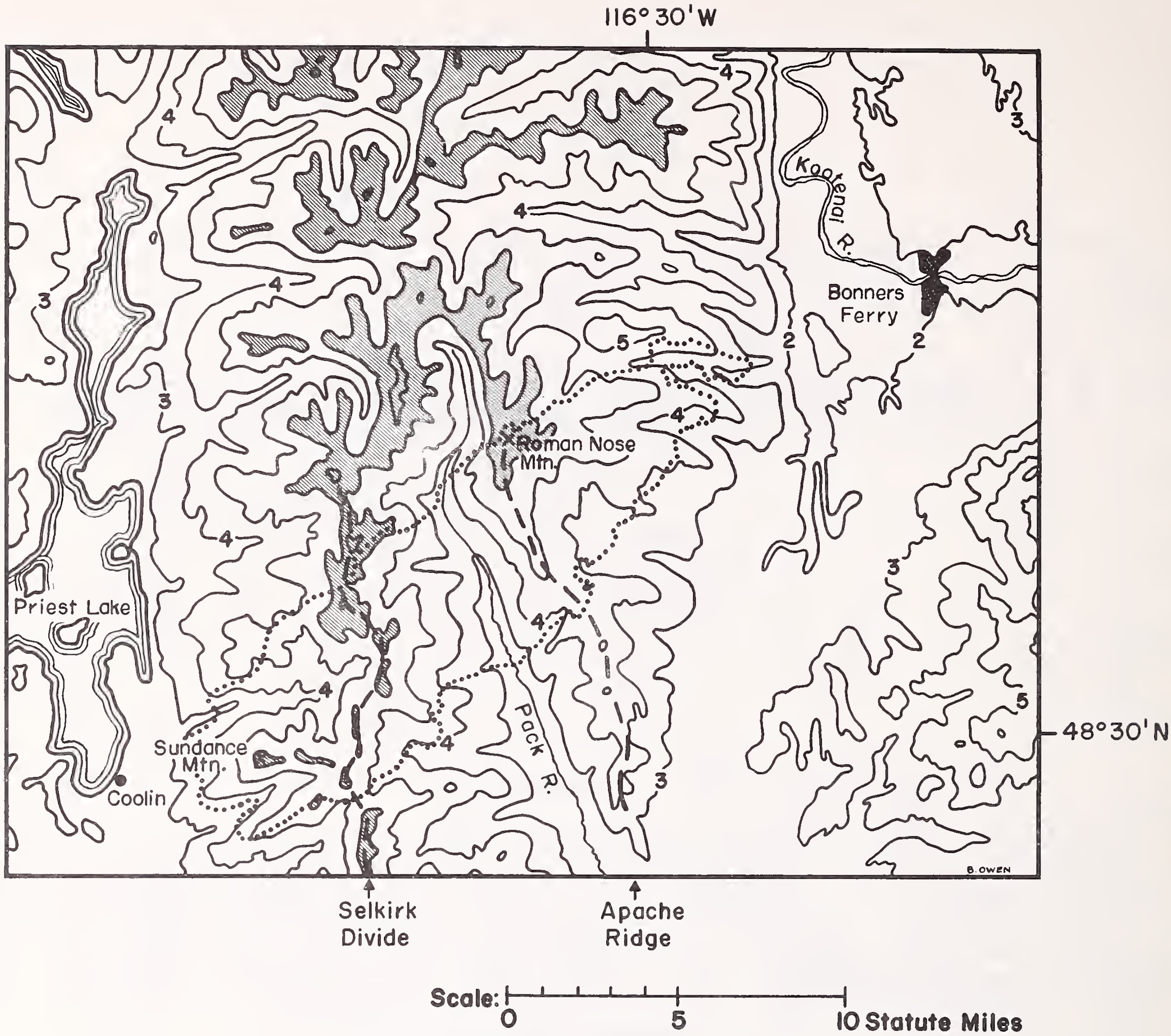

Figure 2.--Detail of Sundance Fire vicinity (area within rectangle of fig. 1; burn area enclosed by dotted line). Contours (solid lines) are drawn at 1,000-ft. intervals (labeled in 1,000 ft. m.s.l.); terrain above 6,000 ft. m.s.l. is denoted by hatching. (From U. S. Geological Survey map, prepared by the Army Map Service, Corps of Engineers, U.S. Army.)

Resumed fire spread, leading to the major run on September 1, began with a several-hour flareup on the night of August 29-30. Flames, apparently wind-driven, jumped the control line and sped downslope in a general westerly direction, burning about 2,000 acres. East to northeast winds, reaching around 15 to 20 m.p.h., were observed at two adjacent mountaintop stations and also by sounding balloon at corresponding levels in the atmosphere above Spokane, Washington. These winds were associated with a cool surface high to the northeast, moving southeastward across Alberta and Saskatchewan. It passed well to the east, and the wind in northern Idaho shifted to light south or southwest on August 31. This ended a fire threat to Coolin, Idaho (fig. 2), but the fire remained uncontrolled; the stage was now set for trouble in the opposite direction as a Pacific weather system (trough and front) approached the coast.

THE SUNDANCE FIRE RUN AND RELATED WEATHER

Meteorological Data

Data sources for our various weather analyses consisted primarily of the ESSA U.S. Weather Bureau (now NOAA National Weather Service) synoptic and hourly meteorological teletype data, and also of reports and hygrothermograph traces from fire-weather stations. These data were furnished by the Missoula office of the Weather Service and several offices of the USDA Forest Service, Northern Region. These were later supplemented by the Northern Hemispheric Data Tabulations (checked data), obtained on microfilm from the National Weather Records Center, Asheville, N.C. Helpful data were also provided by Battelle-Northwest, Richland, Washington. The map analyses presented here are those of the author; guidance toward some of these was provided by maps analyzed by the Weather Service, mostly those received via "facsimile" machine from the National Meteorological Center (NMC), Suitland, Maryland. Surface-map frontal analyses were checked, where possible, against cloud photographs by the ESSA 5 satellite.

The Larger-Scale Weather Pattern

Before examining the fire behavior that constituted the Sundance Fire run, we will shift attention to the larger-scale weather pattern. We may thus trace the evolution of the strong wind conditions in the fire vicinity and also establish a background from which to examine other meteorological factors.

The fire run began around 1400 P.d.t. (equivalent of mountain standard time) September 1, 1967, in the increasing southwesterly airflow ahead of an approaching trough aloft (as well as at the surface). This trough (and deep low center) had been a notable weather-map feature for the preceding several days, and covered the Gulf of Alaska-eastern Pacific Ocean area where it had stagnated between 145° and 150° W. longitude. Its more normal eastward movement resumed on August 31, coinciding with an

increase in the midlatitude Pacific area "zonal index" (strength of upper-level west-east wind component) and was now about 250 nautical miles (n.mi.) off the Washington-Oregon coast. Coupled with the trough was a stationary warm, dry upper ridge located over the Great Basin area. This ridge had very recently extended over all of the western United States and mainland Canada. Also in the picture was a weak Pacific cold front located typically ahead of the upper trough and approaching the coast.

The progress of these features can be followed in a series of 700-millibar (mb.)[2] (approximately 10,000 ft. m.s.l.)[3] maps presented in figures 3 through 8 and the surface maps presented in figures 38 through 43 (Appendix). These 700-mb. maps depict the general wind and temperature field in the lower troposphere (or "free atmosphere"), largely free of frictional effects or irregularities induced by the local terrain. Wind direction at this level is seen to be closely parallel to the height contours, and its speed varies inversely with the contour spacing. Although the analyses use height contours, in effect these may be viewed as isobars on a fixed-height surface. We shall thus refer to the height gradients as pressure gradients, which may be more dynamically descriptive. Figure 9 shows the rather zonal "normal," 30-day averaged (and thus smoothed) 700-mb. airflow at this time of year (mid-August to mid-September). The anomalous, extremely meridional pattern seen on the days prior to the fire run (figs. 3 and 4) was characteristic of much of the mid- and late summer of 1967.

At 0500 August 30 (fig. 3), a strong pressure gradient at 700 mb., between the trough and ridge, was evident offshore and over southeastern Alaska, resulting in observed windspeeds as high as 55 knots. The wind was as yet rather light (5 to 10 knots) in the northern Idaho area (Sundance Fire vicinity denoted by a small circle). The 15 to 20 m.p.h. east to northeast winds occurring in the vicinity of the Sundance Fire flareup a few hours earlier were confined to levels several thousand feet lower--in the gradient set up by the previously mentioned cool surface high. This high moved southeastward on the east side of the upper ridge.

By 0500 September 1, or 9 hr. before the Sundance Fire run began, there was a pronounced 24-hr. increase in 700-mb. pressure gradient over the interior Pacific Northwest (fig. 5, compared with fig. 4); this was the combined effect of the approaching offshore trough and the persisting ridge over the Great Basin. Southwesterly winds had now reached 20 to 25 knots in the Sundance Fire vicinity and 40 knots near the Washington-Oregon coast.

By 1700 on September 1, or 3 hr. after the fire run began (fig. 6), the 700-mb. southwesterly winds reached about 35 knots in the Sundance vicinity. A speed of 50 knots was now observed upwind in northwestern Oregon. At the surface (fig. 40, Appendix), the weak Pacific front had begun dissipating after reaching inland. It was being replaced, however, by a newly formed cold front just east of the Cascade Range in Washington-Oregon and an apparently separate one across southeastern British Columbia. This frontogenesis is reflected in the increased temperature gradient at 700 mb., as the cooler, moister airmass spreading eastward with the trough impinged upon the warm, dry airmass persisting with the ridge over the Great Basin and the Northern Rockies.

The 700-mb. gradient wind in the Sundance vicinity continued to increase during the evening of September 1, reaching its maximum, about 45 knots, around 2300 P.d.t., near the end of the fire run. By this time, the newly formed cold fronts straddled the Idaho panhandle-Sundance Fire area; the southern portion of the Canadian front lagged behind its United States counterpart (fig. 41, Appendix).

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[2]Metric units are used in this paper where it is standard meteorological operational practice in the United States; otherwise, English units are used.

[3]Except where otherwise noted, all elevations mentioned in this paper refer to mean sea level.

Figures 3 through 8.--Analyses of 700-mb. conditions August 30, 1967, through September 2, 1967, and superimposed surface-map positions of fronts (figs. 5 through 8). Height contours are labeled in tens of meters; isotherms (dashed lines) in degrees Celsius. Wind reports are plotted in standard symbolic form, with speeds to nearest 5 knots: tail of arrow (containing "barbs") points in direction from which wind is blowing; each full barb denotes 10 knots of speed (a half barb 5 knots), a pennant 50 knots. Frontal positions 6 hours earlier (figs. 6 through 8) are indicated by dotted lines.

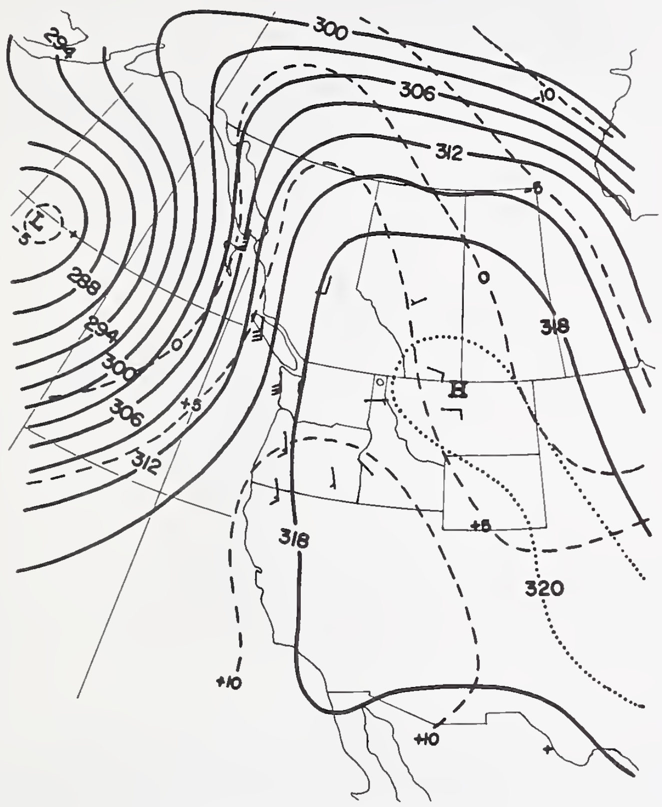


Figure 3.--0500 m.s.t. August 30, 1967.

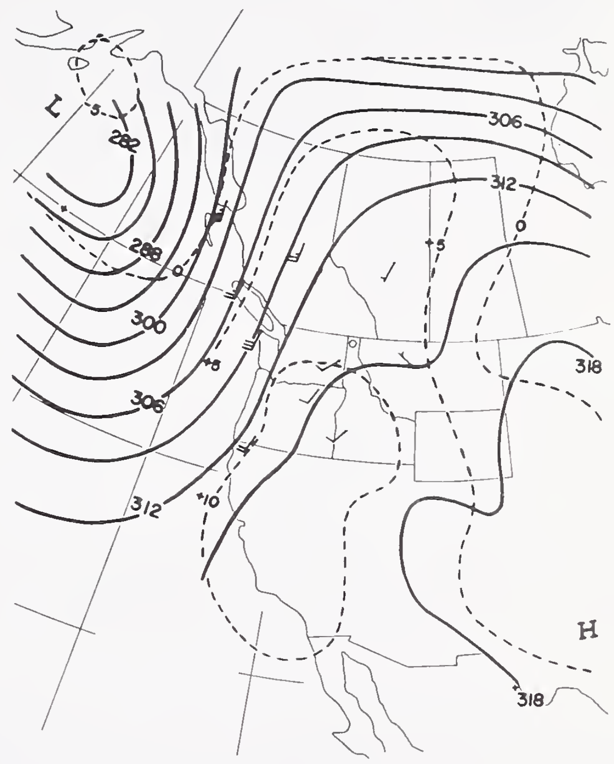


Figure 4.--0500 m.s.t. August 31, 1967.

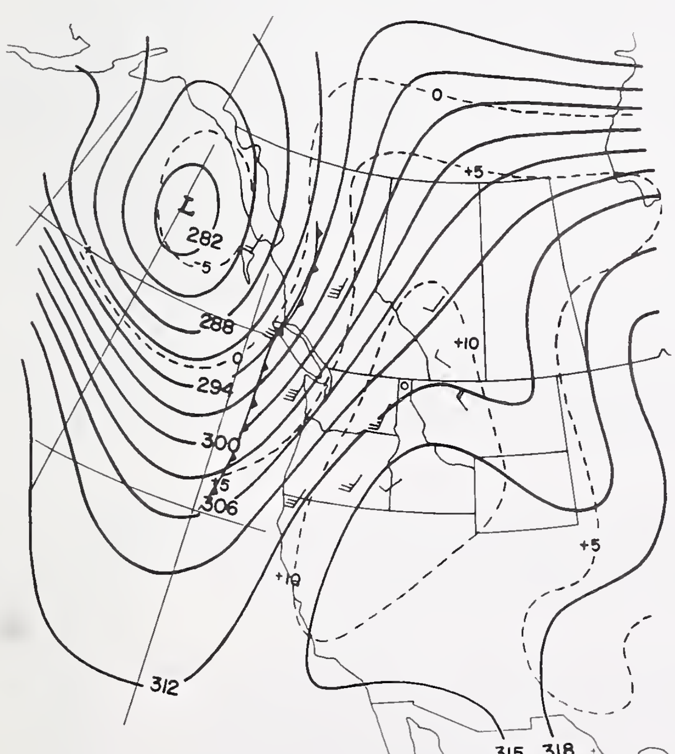


Figure 5.--0500 m.s.t. September 1, 1967.

Figure 6.--1700 m.s.t. September 1, 1967.

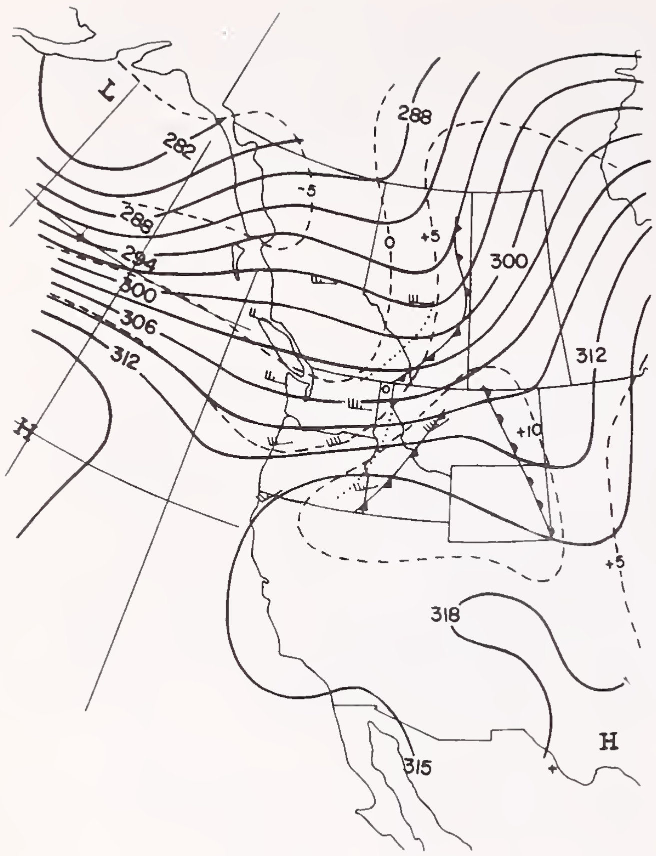


Figure 7.--(0500 m.s.t. September 2, 1967)

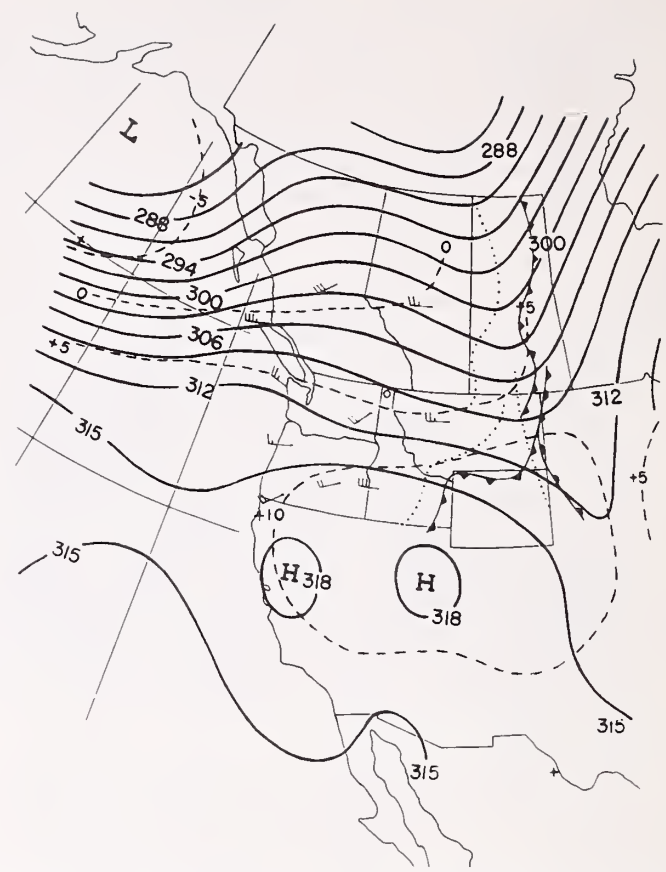


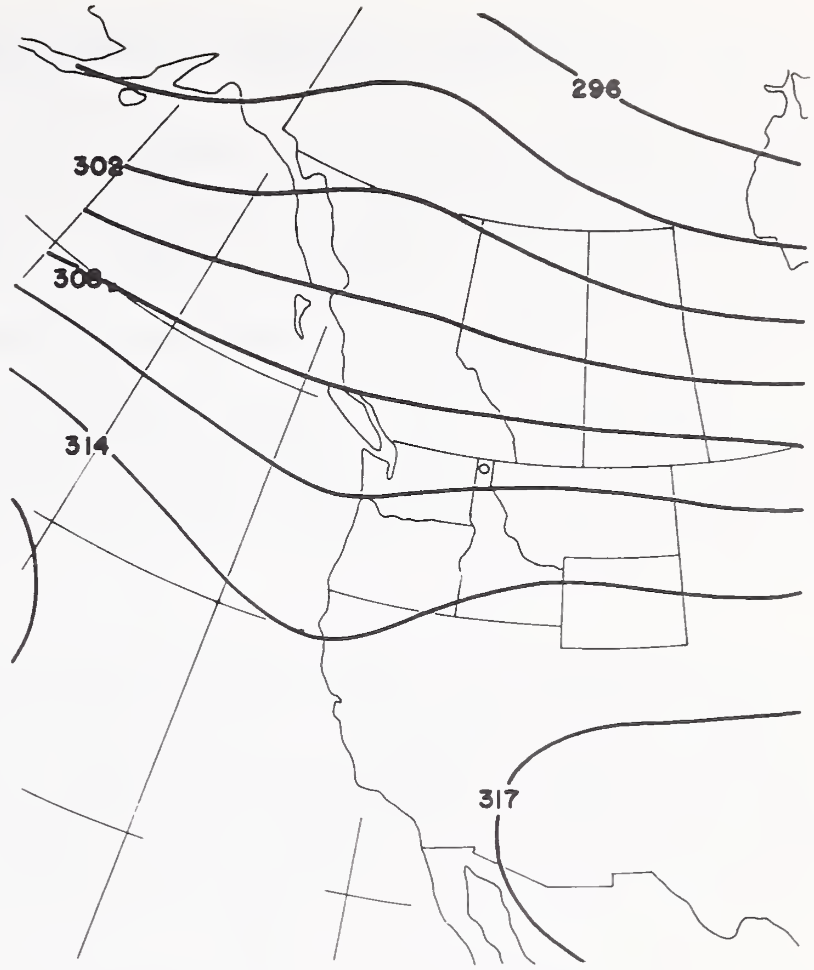
Figure 8.--(1700 m.s.t. September 2, 1967)

A pronounced flattening of the upper trough occurred by 0500 P.d.t. September 2 (fig.7), or 6 hr. after the fire run ended, with the airflow becoming westerly over the Pacific Northwest. Only a small trough remnant could be discerned off the Oregon coast, while to the north the trough appears to have sheared and accelerated as a short wave, now over Alberta. The zone of strongest gradient wind had shifted southward of the Sundance area, where the 700-mb. speed was down to about 30 or 35 knots. The surface cold fronts remained separated, now straddling northwestern Montana (fig. 42, Appendix). Some light rain (and a little thunder) were occurring closely behind the Canadian front, which was just touching the northern Idaho border. No such weather--in fact scarcely any cumuliform cloud development--had occurred thus far with the front in the States (some did occur later in the day in eastern Montana). The Sundance Fire area appears to have remained in a latitudinal gap between the two fronts. Or, at least, the portion of a frontal zone which may have passed through this area was too diffuse to define at the surface. The surface frontal complexity or distortion, suspectedly induced by topography, is not reflected in the 700-mb. temperature analysis; this may be partially attributed to the much coarser upper-air station network (radiosonde observations 250 n.mi. or more apart). Significance of the analyzed United States front will be discussed in a later section.

By 1700 P.d.t. on September 2 (fig. 8), little remained of the trough in the Pacific Northwest; instead, a tendency for renewed ridging appeared. The surface fronts, generally steered by the upper flow, had moved well to the east.

Summarizing the observed and gradient windspeed indications from the individual 700-mb. maps, the areas of strongest wind aloft, preceding and during the fire run, are outlined in figure 10. A speed of 40 knots has been chosen as the lower limit for inclusion. Rather evident from the composite is a gradual southeastward to east-southeastward progression of such wind, which reached the Sundance Fire area around 2300 P.d.t. September 1.

Figure 9.--Normal 700-mb. height (converted to tens of meters), mid-August to mid-September. (From NOAA National Weather Service, Extended Forecast Division.)



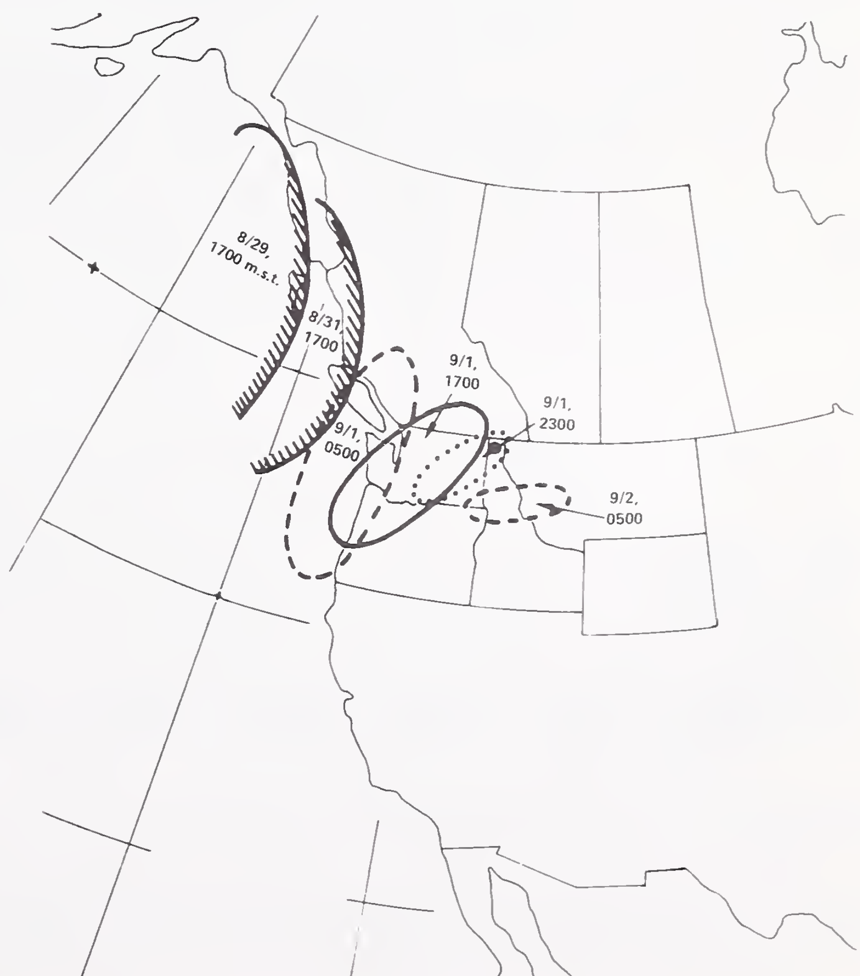


Figure 10.--Areas of strongest wind ($\geq$40 knots) at 700 mb., Aug. 29 to Sept. 2, 1967.

Observed Wind in Northern Idaho Vicinity

1. *Lower free-atmosphere wind.* Figure 11 presents a time graph of windspeed at somewhat lower levels of the free atmosphere, close to the elevations of the mountains and ridges in the Sundance Fire area. It is based on 6-hourly observations and shows the windspeed averaged over the 5,000-7,000 ft. m.s.l. layer at Spokane, Washington (about 70 statute miles southwest of Sundance Mountain), and also, for comparison, at two adjacent stations. These two stations (west and east) are Quillayute, on the northern Washington coast, and Great Falls, Montana.

In this graph (fig. 11), a pronounced peak in windspeed is seen to have occurred at all three stations, progressing eastward with approximately 12-hr. spacing between stations. The observed peak speeds were fairly similar, the 45 knots at Spokane being highest by 7 knots. Together with figure 10, this graph shows that the strong winds in the Sundance area were part of a broad-scale, sustained feature which was trackable at least in retrospect.

Sustained windspeeds of 40 knots or greater at these low tropospheric levels (5,000 to 7,000 ft. m.s.l.) appear to be quite exceptional in the Sundance area during the fire season. Eleven years of data at Spokane--June 15-September 15 during 1957-1967--indicate an average occurrence (based on four wind soundings daily) of only 1 or 2 days (24-hr. periods) per season with such observed windspeeds. The highest observed speed at 5,000 ft. was 55 knots on September 1, 1961, at 1000 P.s.t.

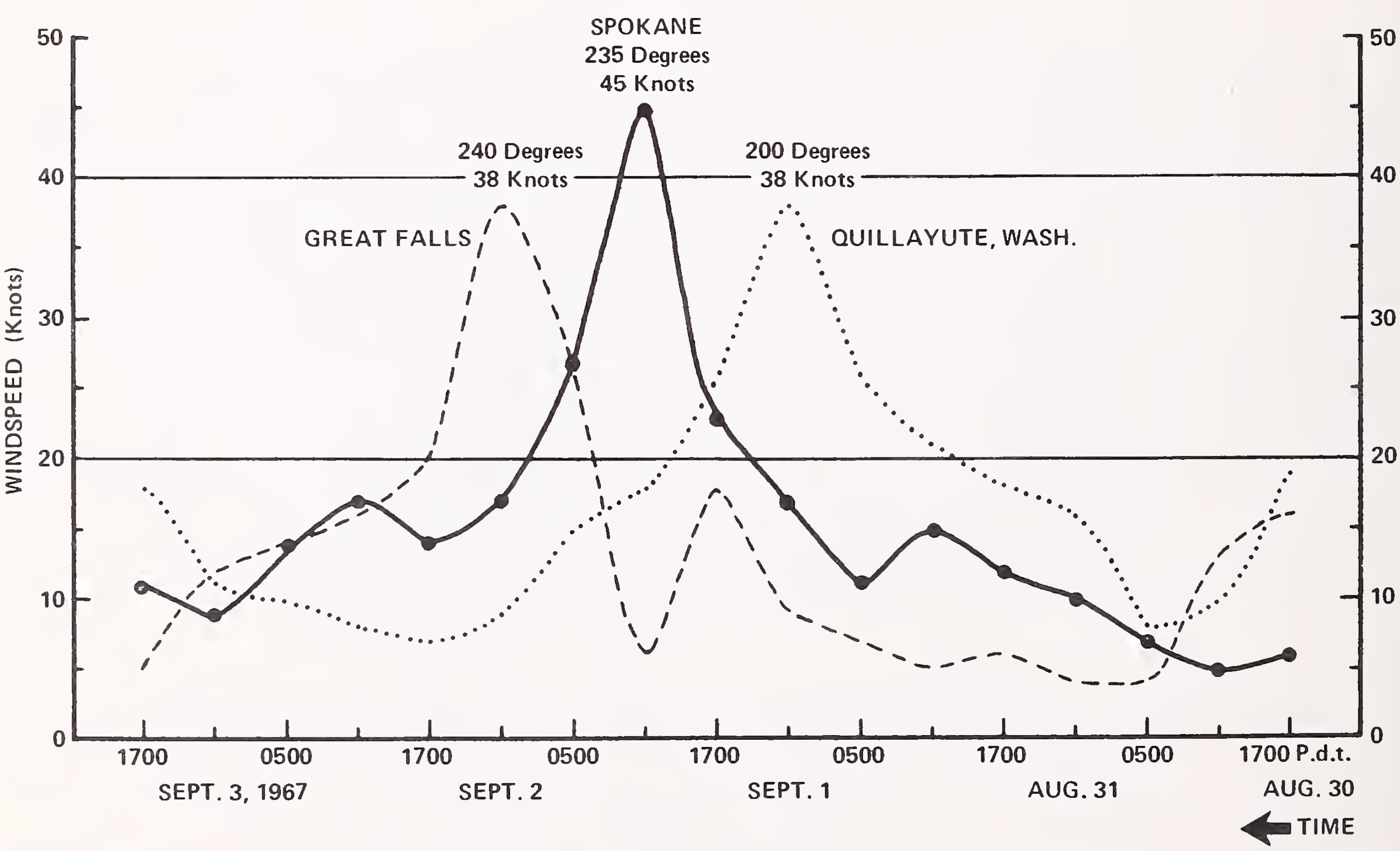


Figure 11.--Time graph of 5,000- to 7,000-ft. m.s.l. layer-mean windspeed, Spokane and two adjacent stations, August 30 to September 3, 1967.

The days having these 40-knot windspeeds occurred almost invariably in June or September. This seems to reflect a more northward confinement and somewhat weaker intensity of the strongest pressure gradients during July and August. In all but one of the 12 cases actually found in the 1957-1967 sample (soundings were made only two or three times per day in 5 of the years) the wind direction was southwesterly or west-southwesterly with an upper trough (major or short wave) located near the Washington coast. However, amplitude of the troughs varied, as did their history. There were frontal passages from the west in half the cases.

2. *Winds at higher levels*. The relation of the lower-tropospheric winds to those at higher levels before, during, and following the Sundance Fire run may be seen in figure 12. This figure is a time-height cross section of winds observed above Spokane. The observations are by rawinsonde (using radio tracking of a balloon) at 0500 and 1700 P.d.t. and by pilot balloon, or "pibal" (using single-theodolite tracking), at 1100 and 2300 P.d.t. Although "pibal" winds are more prone to error than those obtained by rawinsonde, the speeds and directions from the two methods appear rather compatible in this figure.

In general, we see in figure 12 that the strong lower-level winds around the time of the fire run were tied in with increasing and peak speeds at all levels of the troposphere. A shift in wind direction from southwest to west, related to trough passage and flattening, followed the peak at levels from 8,000 ft. upward. However, little change in wind direction occurred at lower levels where it remained southwesterly; this may represent a relatively local condition related to a lee-trough tendency in these levels east of the Cascades. Concern about a possible wind shift to northwest in the lower levels, creating a fire front 20 miles wide (Anderson 1968), fortunately was not realized.

3. *Surface wind*. Figure 13 gives a closer look as to how the winds aloft might relate to those actually observed or expected at ground- or tree-level locations in the Sundance Fire area. It compares the free-atmosphere windspeeds observed above Spokane (averaged for two layers, 5,000-7,000 ft. and 10,000-12,000 ft. m.s.l.) with the speeds at two mountaintop locations in or near the fire area; also included are the speeds atop a 400-ft. tower at Hanford, Washington (Atomic Energy Commission), ground elevation 700 ft. m.s.l., about 120 statute miles southwest of Spokane.

Winds in mountainous areas can, of course, vary considerably within short distances according to exposure to the general airflow. Although surface friction acts to reduce the windspeed near the ground, terrain-induced turbulence (increasing with gradient windspeed) may bring strong gusts (carrying down faster moving air from higher levels). Locally, winds may be increased by terrain-enforced convergence of airflow.

This graph (fig. 13) uses the most complete wind data available in the Sundance Fire vicinity which was obtained from Lunch Peak, at 6,400 ft. 20 miles to the southeast. Here, hourly observations (except for several nighttime hours) were made at a mobile fire-weather station actually in operation for an adjacent fire (the Plume Creek Fire). A rather abrupt rise in this station's windspeed may be noted between 1600 and 1700 P.d.t. September 1, or early in the Sundance Fire run. Winds from the southwest reached steady speeds of about 35 m.p.h. at 1800 and 1900 P.d.t.; gusts (not plotted) reached 50 to 55 m.p.h. These gusts corresponded closely to the Spokane windspeeds observed at 10,000 to 12,000 ft.

Roman Nose Lookout, at 7,264 ft. on the northern edge of the fire, had a 12-m.p.h. southerly wind at the regular 1600 P.d.t. fire-weather observation time; a steady speed of 35 to 40 m.p.h. from the southwest was reported at 2015 P.d.t. (just before the advancing fire caused evacuation of the tower). A lookout atop 7,235-ft. Mt. Henry, in extreme northwestern Montana, reported winds averaging 40 m.p.h. and gusting to 60 m.p.h. (time not given).

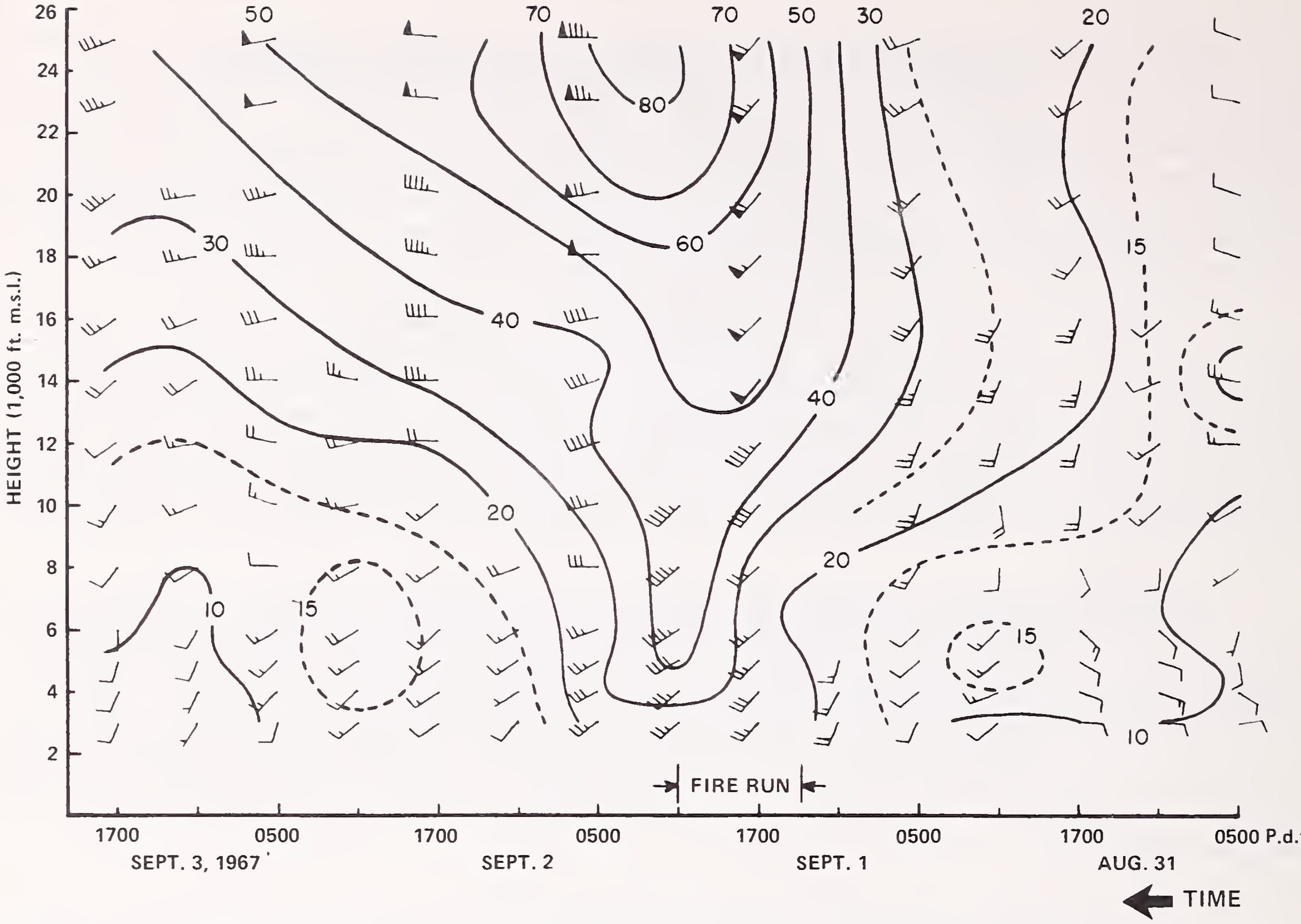


Figure 12.--Time-height section of winds aloft (knots) at Spokane, Wash., August 31 through September 3, 1967. Wind representation as explained previously; top of diagram is assumed to be north. Isotachs are drawn at 10-knot intervals except for dashed line.

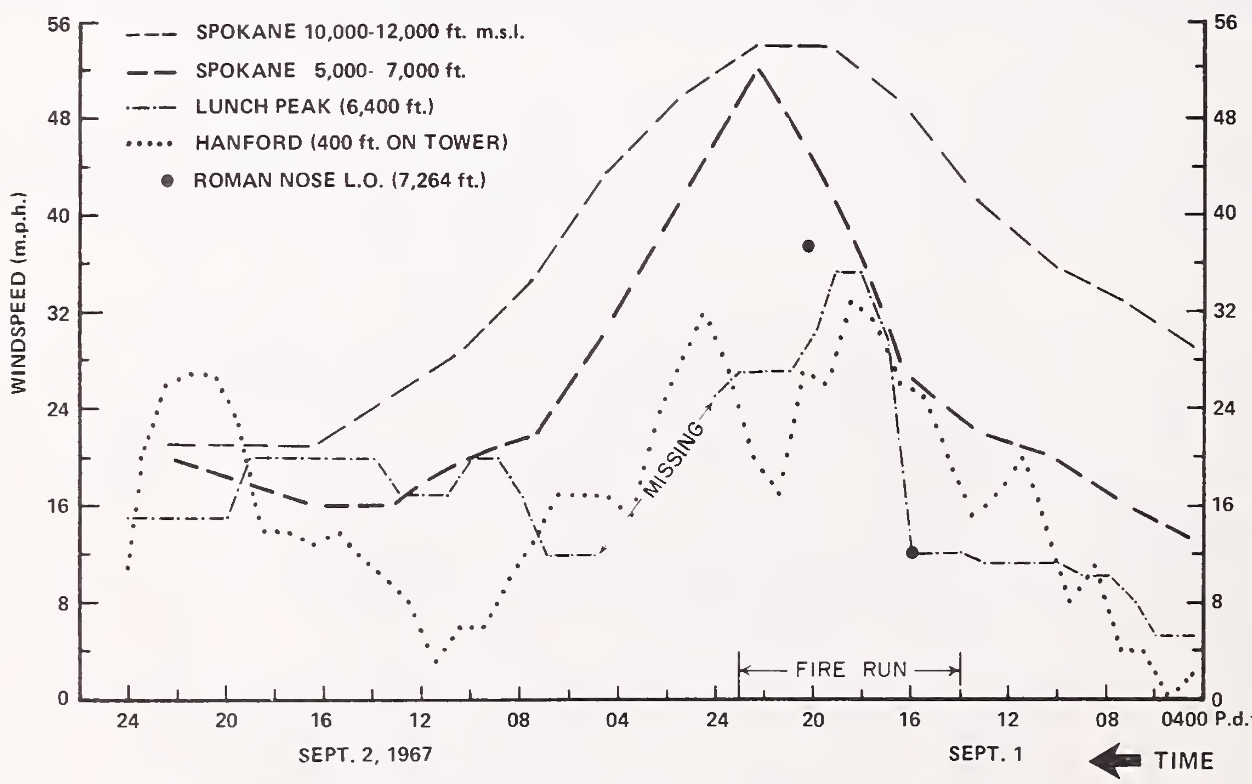


Figure 13.--Time graph comparison of free-atmosphere windspeeds at Spokane and windspeeds at three surface (or tower) observation points, September 1-2, 1967.

Among the mountaintop fire-weather stations reporting once daily, four of the seven located in northeastern Washington (at elevations ranging between 3,800 and 5,900 ft.) had 1600 P.d.t. windspeeds between 27 and 33 m.p.h. Windspeeds at five such stations in the northern Idaho panhandle (at elevations between 5,200 and 6,400 ft.) were as yet only between 12 and 16 m.p.h. To illustrate possible terrain-exposure effects, Squaw Peak (6,200 ft.), Montana, nearby to the southeast, already had 29 m.p.h. at this time.

The windspeeds recorded at Lunch Peak and the two available from Roman Nose Lookout follow reasonably well the 5,000-7,000 ft. wind trend at Spokane during the late afternoon and early evening of September 1. The same can be said for the windspeeds at Hanford. The Lunch Peak and Hanford speeds depart considerably, however, from those above Spokane later in the evening. This discrepancy probably involves variations in the vertical turbulent transfer of momentum through the "friction layer." This layer, below the "free atmosphere," would extend mainly to near 5,000 ft. at Spokane and to correspondingly higher altitudes above the mountainous area in northern Idaho.

Also to be considered is the possibility that a vertical exchange of momentum within the free atmosphere, via subsidence, contributed in part to the lower-tropospheric windspeed, e.g., the 5,000-ft. maximum speed shown for Spokane. A mechanism for this will be considered in a later section. The 5,000-ft. maximum observed at Spokane was supergradient by about 15 knots, according to the Weather Service NMC 850-mb. analyses for the bracketing 12-hourly map times. The maximum at Quillayute and Great Falls also appeared supergradient. Reanalysis of these maps, however, using a 30-m. height-contour interval instead of the original 60 m., gave much closer gradient support to the observed 5,000-ft. winds. The departure from gradient speed was reduced to about 5 knots. At 10,000 ft. the observed winds were in accord with the pressure gradient (which, however, can adjust to initially supergradient speeds).

Estimated Course of Windspeed and Relative Humidity in Sundance Fire Area

For use in examining the behavior of the Sundance Fire run, figure 14A shows time graphs of windspeed and relative humidity estimated for the fire area. Because of the expected variations according to local topography, only a general picture is given; the frame of reference is the largely hypothetical free atmosphere at an intermediate terrain elevation (5,000 ft.).

The wind graph is adapted from the analysis of Spokane winds in figure 12, allowing for a slight time lag. This lag, estimated from the observed surface winds and spatial differences in pressure gradient on the 700-mb. maps, did not exceed 1 hour and was adjudged to be zero after the time of maximum wind.

The relative humidity values given here are actually a compromise between those in the free atmosphere and those observed near ground level on a ridge or mountaintop. We might call them "modified" free-atmosphere values. They were derived by use of Spokane surface and radiosonde observations and the hygrothermograph charts from two mountain locations: Gisborne Mountain Lookout (5,500 ft., about 10 miles south of the Sundance Fire) and Big Spot mobile weather station (on a ridge at 6,600 ft., about 25 miles north of the fire). Generally, good consistency was found among the temperature and humidity (converted to mixing ratio) tendencies from the above data sources, as shown in figures 15 and 16. The Lunch Peak data, however, were not used here; the observed temperature behavior there showed a discrepancy with that at the above stations and also atop Sunset Peak, Idaho (6,400 ft., about 70 miles south-southeast of the fire), and was not considered representative for the general area.

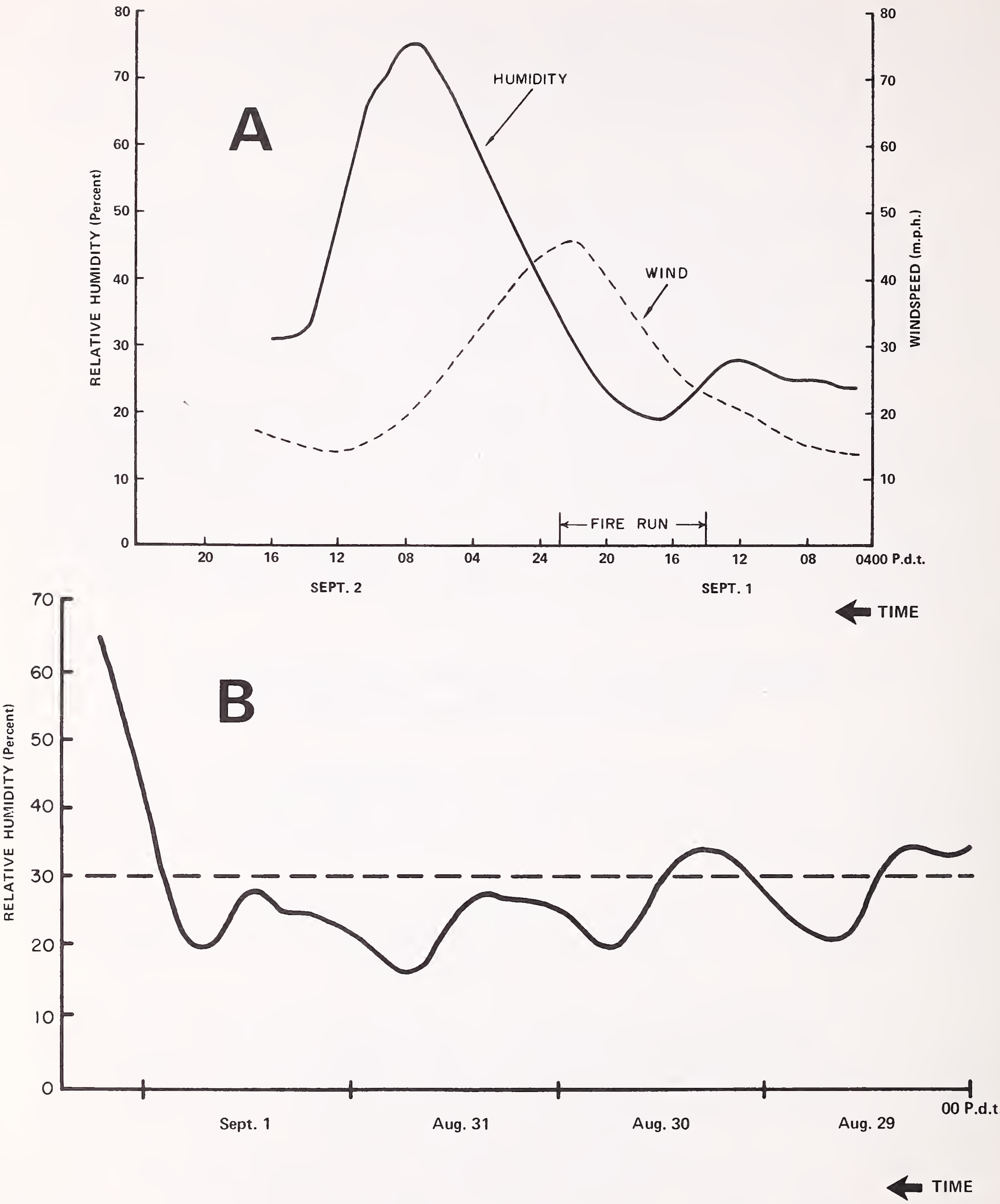


Figure 14.--A. Time graph of estimated gradient windspeed and "modified" free-atmosphere relative humidity at 5,000 ft., Sundance Fire area, September 1-2, 1967 (top panel); B. relative humidity for August 29-September 1, 1967 (bottom panel).

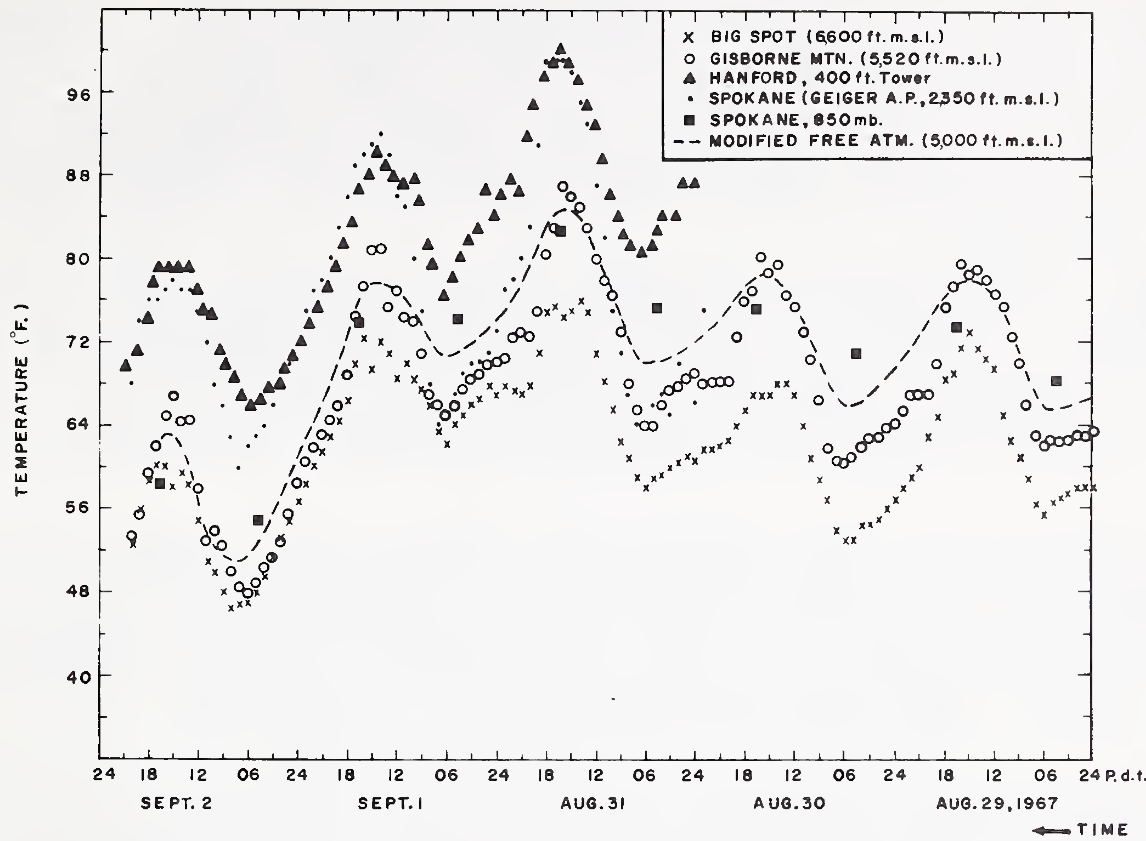


Figure 15.--Temperatures (°F.) at Spokane (surface and 850 mb.) and two mountaintop locations in northern Idaho, August 29 through September 2, 1967. Data from tower at Hanford, Wash., are also included. Dashed line shows adapted curve for "modified" free atmosphere.

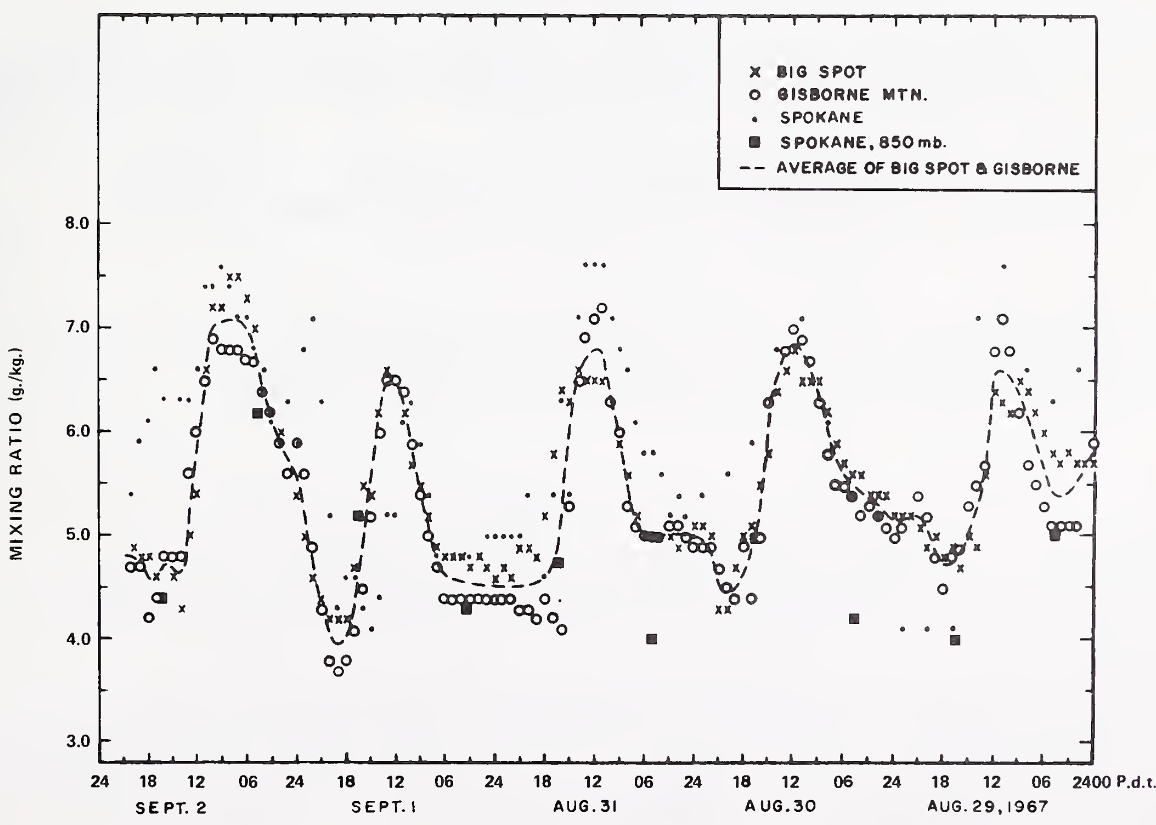


Figure 16.--Mixing ratios (g./kg.), computed from dewpoints and equivalent pressure altitudes of stations, at Spokane (surface and 850 mb.) and two mountaintop locations in northern Idaho, August 29 through September 2, 1967.

A relative humidity threshold of about 30 percent has been found empirically by some researchers to be critical in the preconditioning of fine fuels. A look at figure 14B shows the low relative humidity that persisted both day and night on the dates immediately preceding the Sundance Fire run. As can be seen in figure 14A, the estimated relative humidity on the date of the fire run, September 1, remained below 30 percent until 2200 P.d.t. A steady increase then raised the value to 75 percent on the following morning. This overnight increase came with the advection of a Pacific airmass, which was both cooler and moister.

Although the mixing ratio nearly doubled overnight during September 1-2 (fig. 16), it was primarily the decrease in "modified" free-atmosphere temperature (to near 50° F. at 5,000 ft.) that brought about the large increase in relative humidity. Given the same early morning (0600 P.d.t.) temperature as on the several preceding dates, i.e., about 68° F., the observed increase in mixing ratio to 7.0 g./kg. would have served to raise the relative humidity at 5,000 ft. to only 40 percent.

Mixing ratio values of approximately 7.0 g./kg. may also be seen on the preceding dates in figure 16. These values occurred around noon and were apparently part of a diurnal regime near the ground associated with fair, quiet weather. Values at the two mountain locations were about as high as those at Spokane (surface); little, if any, lag in time of occurrence may be discerned. The Spokane radiosonde data indicate generally lower values in the free atmosphere (850 mb.) on these dates.

This diurnal regime on the mountains appears to be at least partly related to the upward transport of water vapor by the daytime upslope breezes or by convective updrafts. In this respect, a favorable upward gradient of ambient (free-atmosphere) mixing ratio, around 2 g./kg. between the 900- and 800-mb. levels, was present in the Spokane soundings. Under stronger wind conditions, as on September 1-2, the mountaintop mixing ratio should more closely correspond to that of the ambient atmosphere.

Fire Behavior During the Run

Quoting from figures 14A and 15 and from Anderson (1968), plus additional wind data, we will now follow the salient behavior features of the Sundance Fire run. The run, we recall, began around 1400 P.d.t. September 1, 1967. Windspeeds at neighboring Lunch Peak (6,400 ft.) and Big Spot (6,600 ft.) at this time averaged only 10 to 15 m.p.h. Free-atmosphere windspeed at 5,000 ft. was 20 m.p.h. At 10,000 ft., it was 35 m.p.h. "Modified" free-atmosphere relative humidity at 5,000 ft. was 25 percent; temperature was 78° F.

Under the already critical relative humidity conditions which remained below the value of 30 percent, the ensuing rate of spread was found by Anderson (1968) to be strongly influenced by terrain features and wind, either singly or in combination. Thus, early in the run (at 1500 to 1600 P.d.t.), upslope terrain exposed to southwesterly airflow allowed a crowning fire to become established at relatively moderate windspeeds on the west side of 6,000-ft. Selkirk Divide (fig. 2). Surface windspeeds at 1600 P.d.t. at Lunch Peak and Big Spot averaged between 13 and 18 m.p.h., gusting to 28 m.p.h. at the latter station. The free-atmosphere windspeeds were 25 m.p.h. at 5,000 ft. and 40 m.p.h. at 10,000 ft.; temperature and relative humidity at 5,000 ft. were 77° F. and 20 percent.

The fire front slowed at the Selkirk Divide, partly due to the effect of backing spot fires. Then, between 1700 and 1800 P.d.t., as the wind became strong enough to push a crowning fire downslope, the front raced down the east side of the Divide toward the Pack River to about 4,000 ft. Southwesterly winds atop Lunch Peak had by 1800 P.d.t. reached an average 35 m.p.h. with gusts to 55 m.p.h. Big Spot had 20 m.p.h. southerly winds with gusts to 30 m.p.h. The difference here appears at least partly related to the upwind topography. Free-atmosphere winds continued from the southwest, 33 m.p.h. at 5,000 ft. and 45 m.p.h. at 10,000 ft.; temperature and relative humidity at 5,000 ft. were 73° F. and 20 percent.

Farther down toward the Pack River, situated at about 3,000 ft., the fire front slowed once again; the wind had less effect here, the slopes were steeper, and indrafts countered the surface wind. However, fire whirls, possibly triggered by turbulent indraft winds, caused extensive blowdown and tree breakage in this area. Beyond the Pack River, shortly before 2000 P.d.t., there followed a sharp increase in fire development and rate of spread on the west slope of Apache Ridge (fig. 2), which reaches 5,000-6,000 ft., leading to the fire's most rapid advance. The main front swept up and over the ridge at sustained rates as high as 6 m.p.h. This increase was attributed to convective and radiant preheating of fuels (aided by the upslope) and to firebrands, as well as movement once again of the fire front into the wind's influence. Southwesterly winds had decreased slightly atop Lunch Peak, averaging 25 to 35 m.p.h. at 2000 P.d.t., with gusts to 50 m.p.h. (the Big Spot observations had ended for the day). They continued to increase, however, in the free atmosphere, reaching 40 m.p.h. at 5,000 ft. and 50 m.p.h. at 10,000 ft. Temperature and relative humidity at 5,000 ft. were 68° F. and 23 percent.

From 2000 to 2200 P.d.t., the fire advanced across several drainages east of Apache Ridge. At first it was wind-driven but, as previously, the wind effect and rate of spread decreased as lower elevations, down to about 3,500 ft., were reached. There at the lower elevations, the run ended at about 2300 P.d.t., within about 6 miles west-southwest of Bonners Ferry, Idaho. The fire continued uncontrolled for more than a week afterward until September 10 but made little further advance. As the run was ending, winds atop Lunch Peak were still southwesterly at 25 to 30 m.p.h., gusting to 40 m.p.h.; the free-atmosphere speeds were just starting to decrease and had values of 45 m.p.h. at 5,000 ft. and 52 m.p.h. at 10,000 ft. As the cooler, moister airmass continued to gradually move in, the temperature and relative humidity at 5,000 ft. were now 63° F. and 36 percent.

The termination of the fire run was also influenced by the effects of firebrands and resulting spot fires. These had been quite numerous during the run and played an important role in the fire spread. Burning material was evidently carried as much as 12 miles in advance of the main fire front. Transport may have been effected through a convection column that reached as high as 35,000 ft. at about 2030 P.d.t. Finally, however, the resulting fuel voids in these burned-over areas helped lead to the breakdown of the main fire front.

Additional Meteorological Considerations

1. *Wind profiles, instability, subsidence, and downdrafts.* Additional meteorological factors are stated in the literature to be of potential importance in rapid or "explosive" fire spread. These include (a) the vertical wind profile (or shear), (b) airmass stability or instability, (c) subsidence, and (d) downdrafts from adjacent thunderstorms; the last-named factor may be safely regarded as having been absent in the Sundance Fire case.

In regard to wind profile and instability, there has been a difference of opinion among researchers as to their significance. A decrease in windspeed with height, above a low-level maximum or "jet," was found by Byram (1954, 1959) and Small (1957) to be favorable for the formation of an active, turbulent convection column. A more or less steady increase in windspeed with height was said to usually preclude such activity. Graham (1955) and Syverson[4] found that "blowups," in the form of fire whirlwinds, were not associated with any typical wind-profile type. Graham (1955) found these whirlwinds to be largely a lee-slope phenomenon. Contributing factors were extreme instability established locally in lower levels by the heat of an intense fire and strong

[4]C. E. Syverson. An explosive fire condition. Unpubl. rep. on file at the Northern Forest Fire Laboratory, Missoula, Montana. 1959.

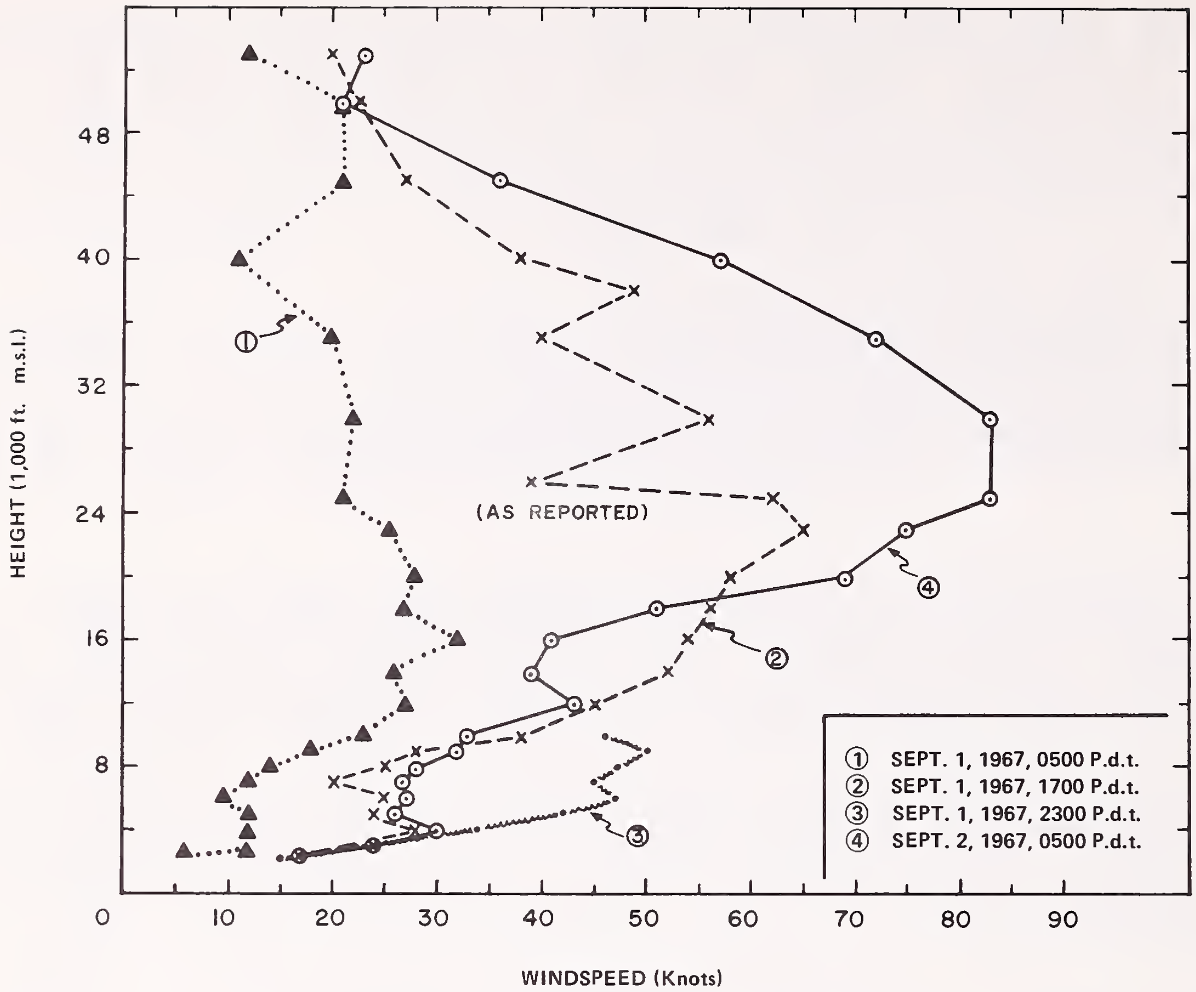


Figure 17.--Wind profiles at Spokane.

winds blowing at right angles across ridgetops. The degree of upper-air instability was said to have little or no effect. Countryman (1964), however, cites the possible effectiveness of an unstable airmass with respect to both fire whirlwinds and the general intensity of burning.

Krumm[5] attributed the explosive burning of fires to severe large-scale subsidence (dry-adiabatic descent of air from high levels), which, often aided by convective (thermal or mechanical) mixing in the lower levels, brought extremely dry air down to the surface. He[6] concluded that such subsidence is most likely to occur on the lee sides of mountain ranges.

The vertical wind shear in the Sundance case may be examined in figure 17. A low-level maximum in speed, at about 4,000 ft., is seen in the three complete (rawin) soundings, particularly the one at 1700 P.d.t. September 1, early in the fire run. The speed increases again a few thousand feet higher up to reach a substantially greater maximum. A more continuous increase in the lower levels, at least up to 8,000 ft., is seen in the short pilot-balloon sounding at 2300 P.d.t. The 1700 P.d.t. profile apparently falls within the criteria of Byram (1959), showing good similarity with one he presents for a case of extreme fire behavior in Virginia. Assuming the Spokane profiles may be applied to the Sundance Fire area (though they would start at somewhat higher elevations), there is a suggested relationship between the indicated low-level "jet" (at 1700 P.d.t.) and the extreme, "three-dimensional" fire behavior that occurred, including the deep convection column. In addition, the strong

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[5] W. R. Krumm. Meteorological conditions which encourage explosive fire spread. Unpubl. rep. on file at Northern Forest Fire Laboratory, Missoula, Mont. 1955.

[6] W. R. Krumm. Aspects of severe subsidence over Medicine Bow fires during July 1955. Unpubl. rep. on file at Northern Forest Fire Laboratory, Missoula, Mont. 1955.

upper-level winds would be quite effective in the apparent long-distance transport of firebrands which were carried aloft in the convection column. By 2300 P.d.t., when the fire run ended, the available lower-level wind profile had become less favorable for extreme fire behavior.

Inferences in regard to both instability and subsidence in the Sundance case may be gained from figures 18, 19, 20, and 21. The first three of these figures show the temperatures and mixing ratios on three successive afternoons as observed above Spokane (to 700 mb.) and at valley and mountaintop fire-weather stations. Figure 21 compares the 12-hourly Spokane temperature and dewpoint profiles, to 400 mb., 1700 P.d.t. August 31 through 1700 P.d.t. September 2.

The lower-tropospheric afternoon temperatures in these figures show, besides a day-to-day cooling trend, lapse rates typically close to dry adiabatic (in fact, super-adiabatic near the surface). Synoptic-scale stability on the day of the fire run was not particularly low, however, if the standard "lifted index" is used. This index, really a guide to potential convective-cloud and storm development, is based on adiabatic lifting of the lowest 3,000-ft. atmospheric layer upward to the 500-mb. (approximately 19,000-ft.) level. Negative values (representing assumed lifted air at 500 mb. warmer than the ambient air temperature obtained by sounding) denote instability. At Spokane, the index values at the five 12-hourly observation times shown in figure 21, beginning at 1700 P.d.t. August 31, were +0, +5.5, +4.5, +3, and +12, respectively. The index at Great Falls on September 1 was ±0 at both 1700 P.d.t. and 2300 P.d.t. The relatively high stability index (+4.5) at Spokane at 1700 P.d.t. on this date was influenced by a slight inversion whose base was at 727 mb. (fig. 21). As shown on page 26 (fig. 26), this inversion layer slopes closer toward the ground eastward toward the Sundance area. Daytime surface heating and adiabatic mixing, however, could have altered the actual lower-level picture there, possibly removing the inversion. From the standpoint of these lower levels, the dry adiabatic or greater lapse rate would certainly not have discouraged fire activity such as intense burning or the whirlwinds which occurred in the Pack River drainage. Further, the great depth of the observed convection column would be influenced by local instability contributed by the fire itself, both from the heat output and moisture product of combustion.

Comparison of potential temperature[7] (fig. 21) indicates that the aforementioned inversion (at 311° to 313° K.) at 1700 P.d.t. September 1 does not represent a continuing downward movement of the apparent subsidence-inversion layer found near 500 mb. (at about 320° to 324° K.) 24 and 12 hr. earlier. Rather, the 1700 P.d.t. September 1 temperature profile primarily reflects the warm airmass overlying the gradually advancing cooler air at lower levels, previously mentioned, which in turn was being modified by surface heating and adiabatic mixing. More extensive cooling through advection is noted by 0500 P.d.t. September 2, followed by subsidence warming aloft 12 hr. later. Large-scale subsidence during the time of the Sundance Fire run is not evident; though, as discussed later, frontal-zone descent of air was possible through at least part of the troposphere.

2. *Significance of cold front and jetstream.* We will examine more fully here the relationship between the strong, gusty winds occurring in the Sundance Fire vicinity and the previously mentioned cold front east of the Cascades. These winds were observed at eastern Washington surface stations by early to middle afternoon (September 1) and progressed into the Idaho panhandle by late afternoon. There, they began approximately 100 to 150 miles in advance of the cold front, though the peak in 5,000-ft. windspeed was reached in late evening when the front may have just passed. At that time, however, the front was rather diffuse or undetectable in the Idaho panhandle area, at least at the surface.

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[7]The temperature a parcel of air would have if it descended dry-adiabatically to the 1,000-mb. level.

Figures 18-20.--Sounding of temperature and mixing ratio at Spokane and corresponding temperatures and mixing ratios observed at fire-weather stations within a 50-mile radius of the Sundance Fire, 1600 P.d.t. Figures alongside points are mixing ratios.

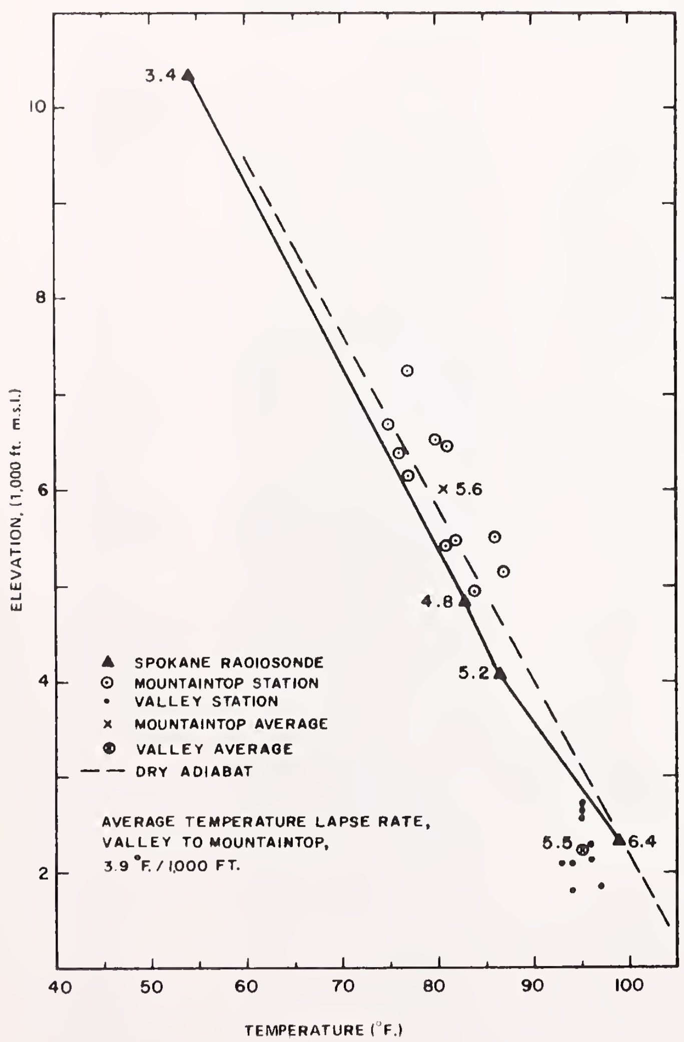

Figure 18.--August 31, 1967.

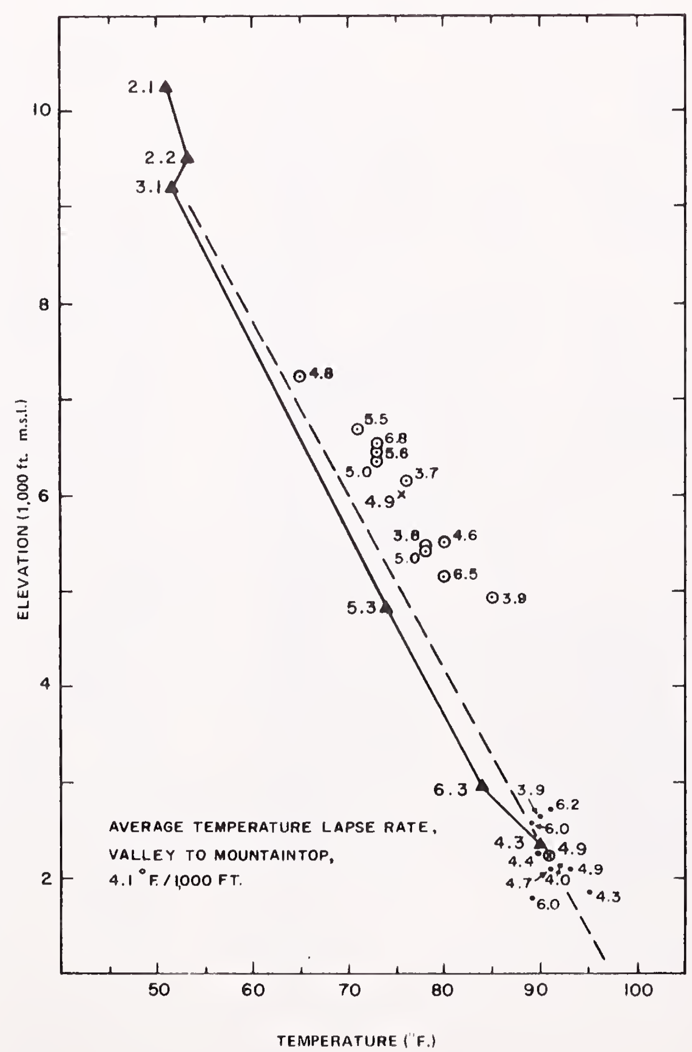

Figure 19.--September 1, 1967.

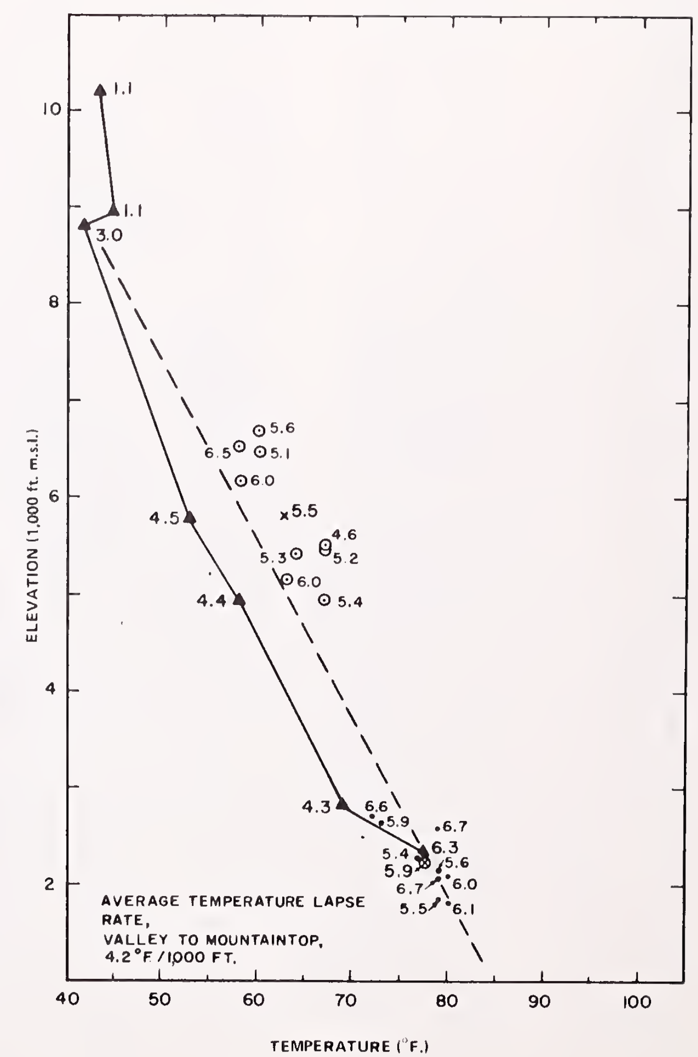

Figure 20.--September 2, 1967.

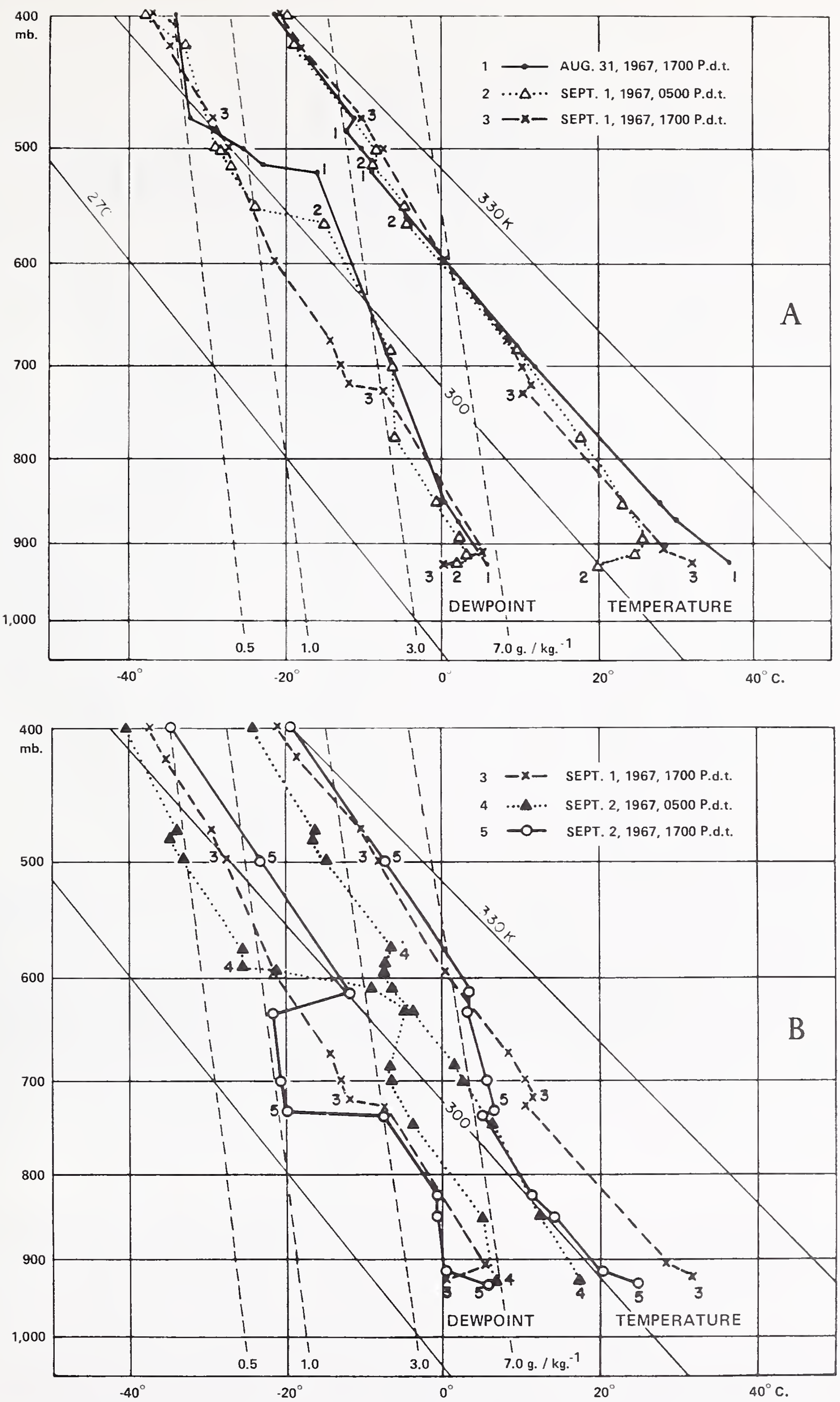

Figure 21.--Temperature and dewpoint profiles at Spokane, 12-hourly observations August 31-September 2, 1967. Thin horizontal lines are pressures (mb.); vertical lines, temperatures (°C.). Thin solid, sloping lines are dry adiabats (°K.). Thin dashed, slightly sloping lines are lines of constant saturated mixing ratio (g./kg.). Top portion (A) shows profiles for September 1, 1700 P.d.t., and for preceding observation times; lower portion (B) shows profiles for September 1, 1700 P.d.t., and succeeding observation times.

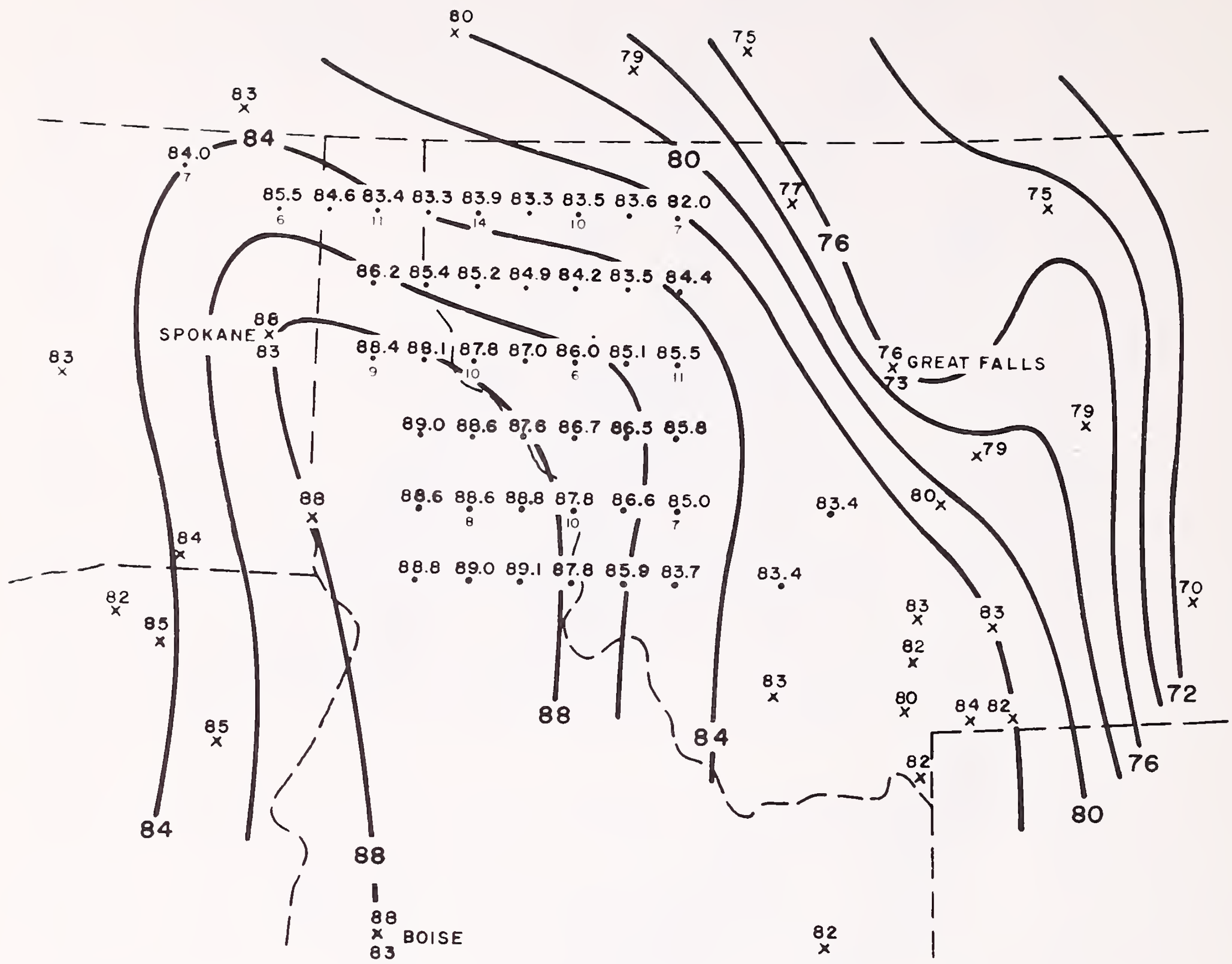

Figure 22.--Analysis of temperature (°F.) reduced to 5,000 ft. m.s.l., 1600 P.d.t. August 31, 1967, based on fire-weather and airways reports. Reduction used a lapse rate (4.3° F. per 1,000 ft.) which gave equal average 5,000-ft. temperatures from the mountain and valley groupings of stations within the grid area. Temperatures shown in grid area are averages from the available stations in overlapping 1° (latitude and longitude) quadrangles and are plotted at central points; the total numbers of stations in the primary quadrangles are denoted by smaller figures below points. Point values of temperatures at neighboring, more isolated stations are plotted above x's; comparative 850-mb. temperatures (at Spokane, Boise, and Great Falls) are plotted below x's.

A cooler-air push (or advection) was already occurring in the afternoon, well ahead of the defined front. This push is reflected in the detailed temperature pattern at 1600 P.d.t. September 1, shown in figure 23, as contrasted with that of 24 hr. earlier (fig. 22). Temperatures used in these analyses were reduced to a common elevation, 5,000 ft.; within the grid area, where the temperatures were reduced from more than 100 fire-weather stations, they were averaged and smoothed (see fig. 22 legend). The values are several degrees Fahrenheit higher than those in the free atmosphere, as indicated by the plotted 850-mb. temperatures.

The cold front in this case appears to represent a steepening of the horizontal temperature gradient (just west of the area covered in fig. 23; see fig. 40, Appendix) embedded within a broader baroclinic[8] region.

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[8]Characterized by existence of horizontal temperature gradient.

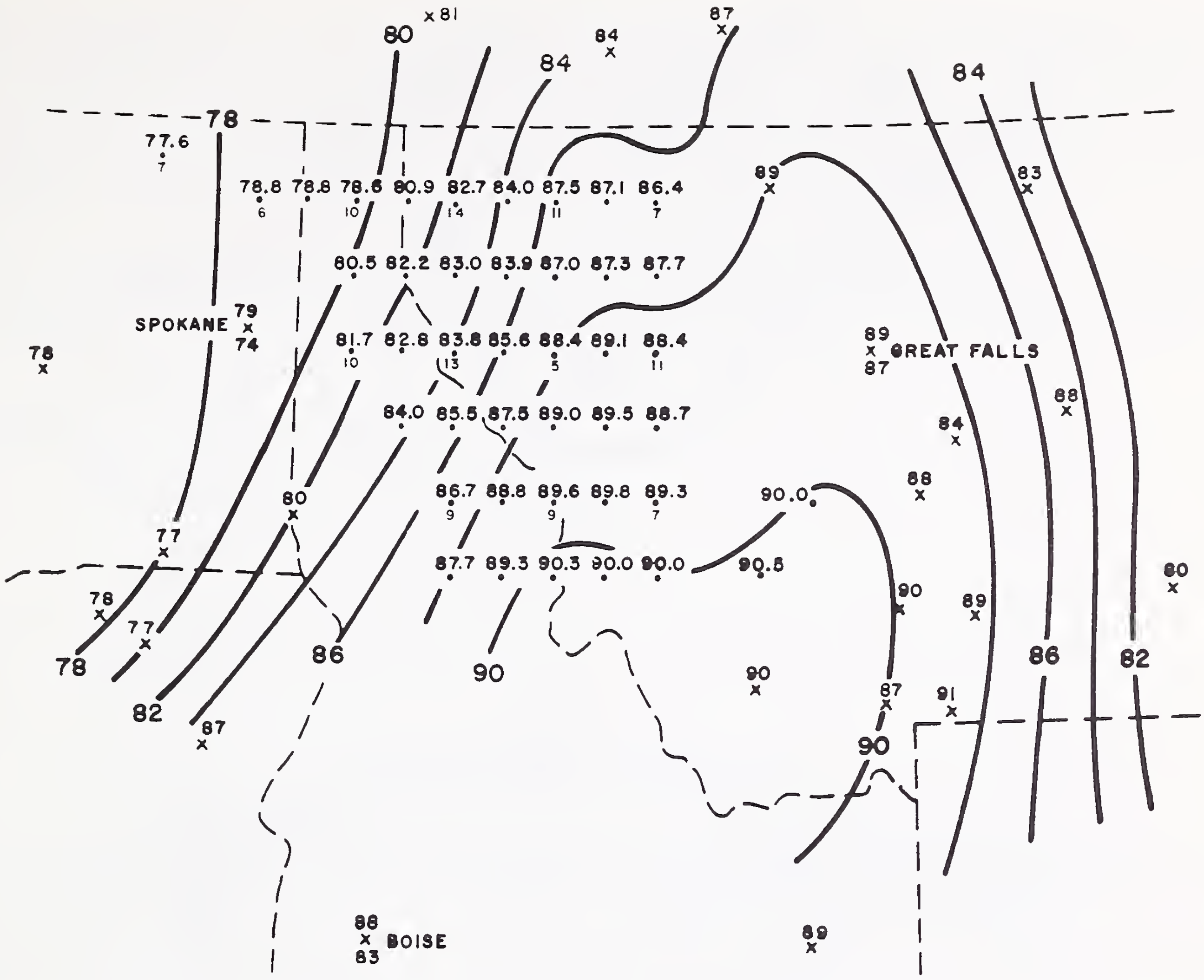


Figure 23.--Same as figure 22, except for 1600 P.d.t. September 1, 1967; reduction uses a lapse rate of 4.4° F., per 1,000 ft.

The actual effect of this diffuse front (or frontal zone) on the Sundance area surface winds would be difficult to prove. The observed gustiness of the wind certainly suggests a contribution by turbulent downward transfer of momentum, which may have been triggered by the frontal zone; but, it could have also been generated mainly by the rough terrain acting upon the increasing gradient airflow. Whatever the frontal role may have been it is evident that the unusually strong surface winds were more ultimately dependent upon the exceptional summertime pressure gradient and winds that existed in the lower troposphere.

The steepened pressure gradient and the cold front, both associated with the approaching trough, may be regarded as individual but related parts of the total weather system. Basic to the system was the juxtaposition of two different (i.e., warm and cool) airmasses. The upper-tropospheric jetstream would also be part of this system.

Reiter (1963) describes a type of sinking motion (or subsidence) occurring within a frontal zone sloping below the jet's core. The drier and also faster-moving air typically reaches the low troposphere (e.g., 850 mb.) on the right, forward side of the jet-axis speed center and hundreds of miles downwind from the upper-tropospheric starting point.

Figure 24 outlines the jetstream axis and isotachs at the 300-mb. (30,000-ft.) level in the Sundance case. At 1700 P.d.t. September 1, early in the fire run, the jet axis was still 200 n.mi. or more to the northwest of the Sundance area. By

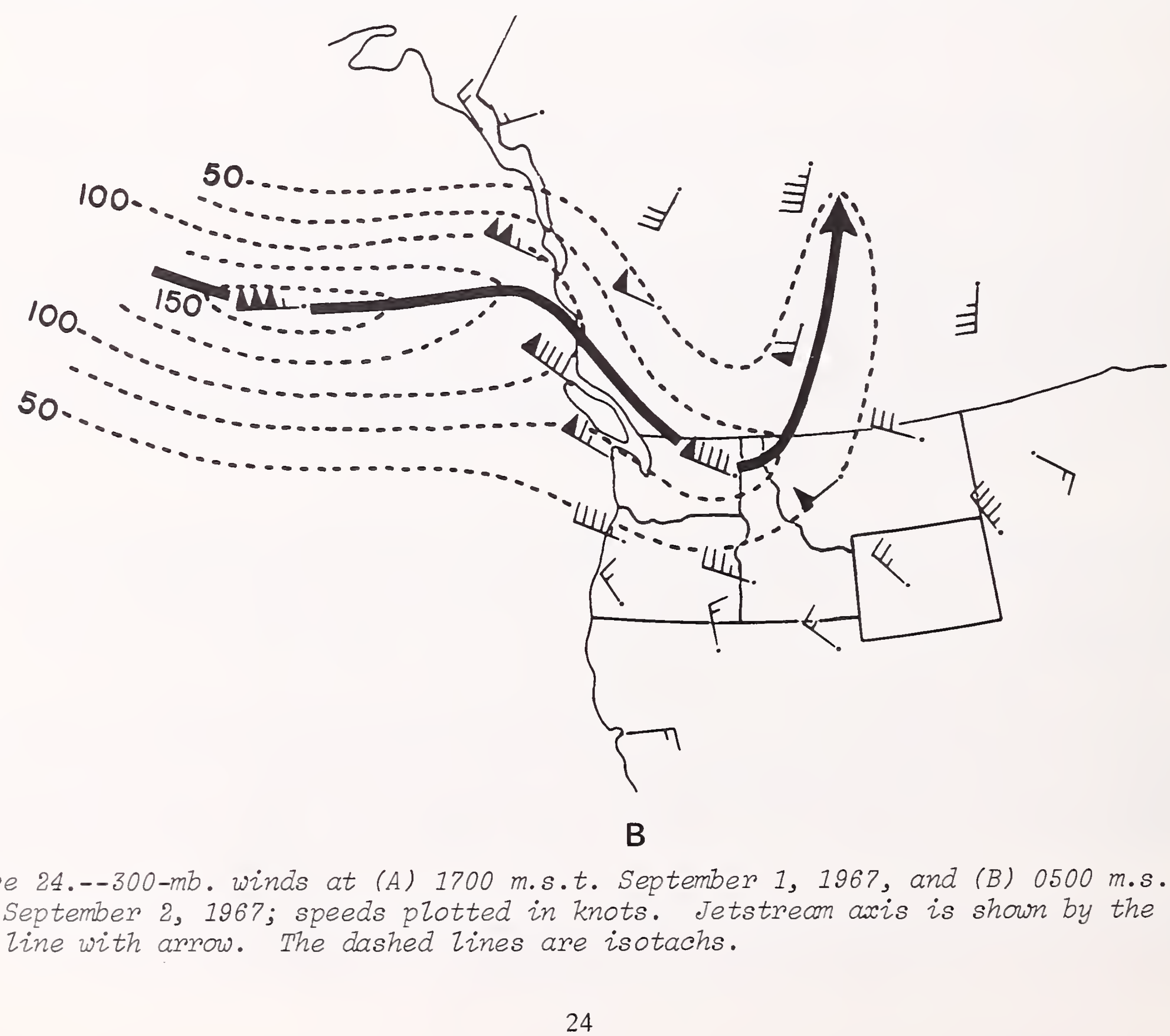


Figure 24.--300-mb. winds at (A) 1700 m.s.t. September 1, 1967, and (B) 0500 m.s.t. September 2, 1967; speeds plotted in knots. Jetstream axis is shown by the heavy line with arrow. The dashed lines are isotachs.

0500 P.d.t. September 2, or 6 hr. after the fire run ended, the southern tip of the axis, located in the pressure trough, was overhead in the Sundance area. A slight center of about 95 knots windspeed may have nosed into the trough, but the main speed center was still well upwind over the Gulf of Alaska. These maps suggest, in a preliminary way, that the Sundance area was in a favorable location for frontal-zone subsidence by early September 2, but less so during the actual fire run.

For further examination of this possible subsidence, figures 25 through 27 show three consecutive 12-hourly cross sections of plotted wind and isentropes of potential temperature along an atmospheric slice extending from the northern Washington

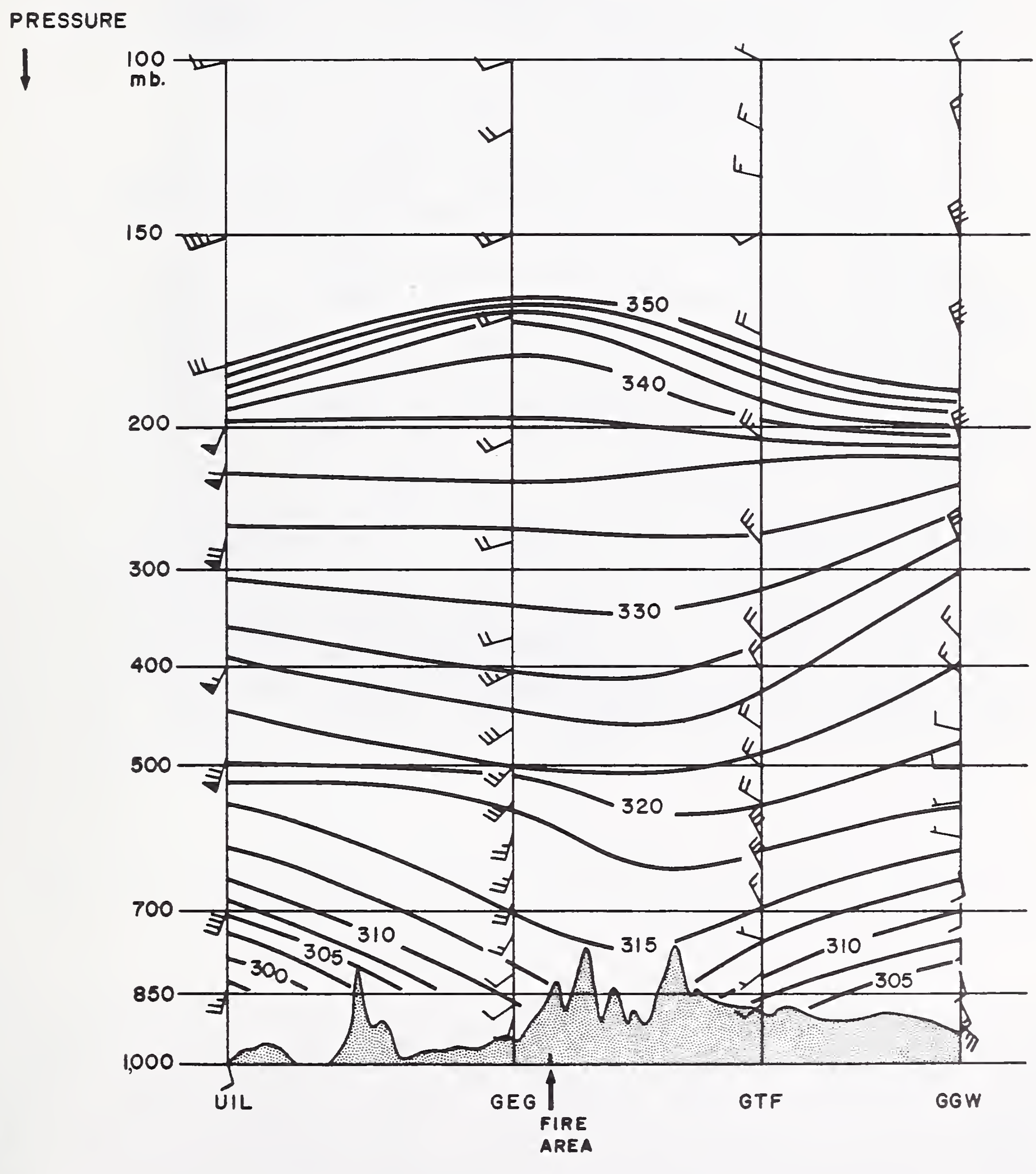


Figure 25.--West-east atmospheric cross section from northern Washington coast to eastern Montana, 0500 P.d.t. (m.s.t.) September 1, 1967, depicting winds and analyzed potential temperature (°K.); isentrope interval 2.5°. (Stations are denoted by their official identification letters.)

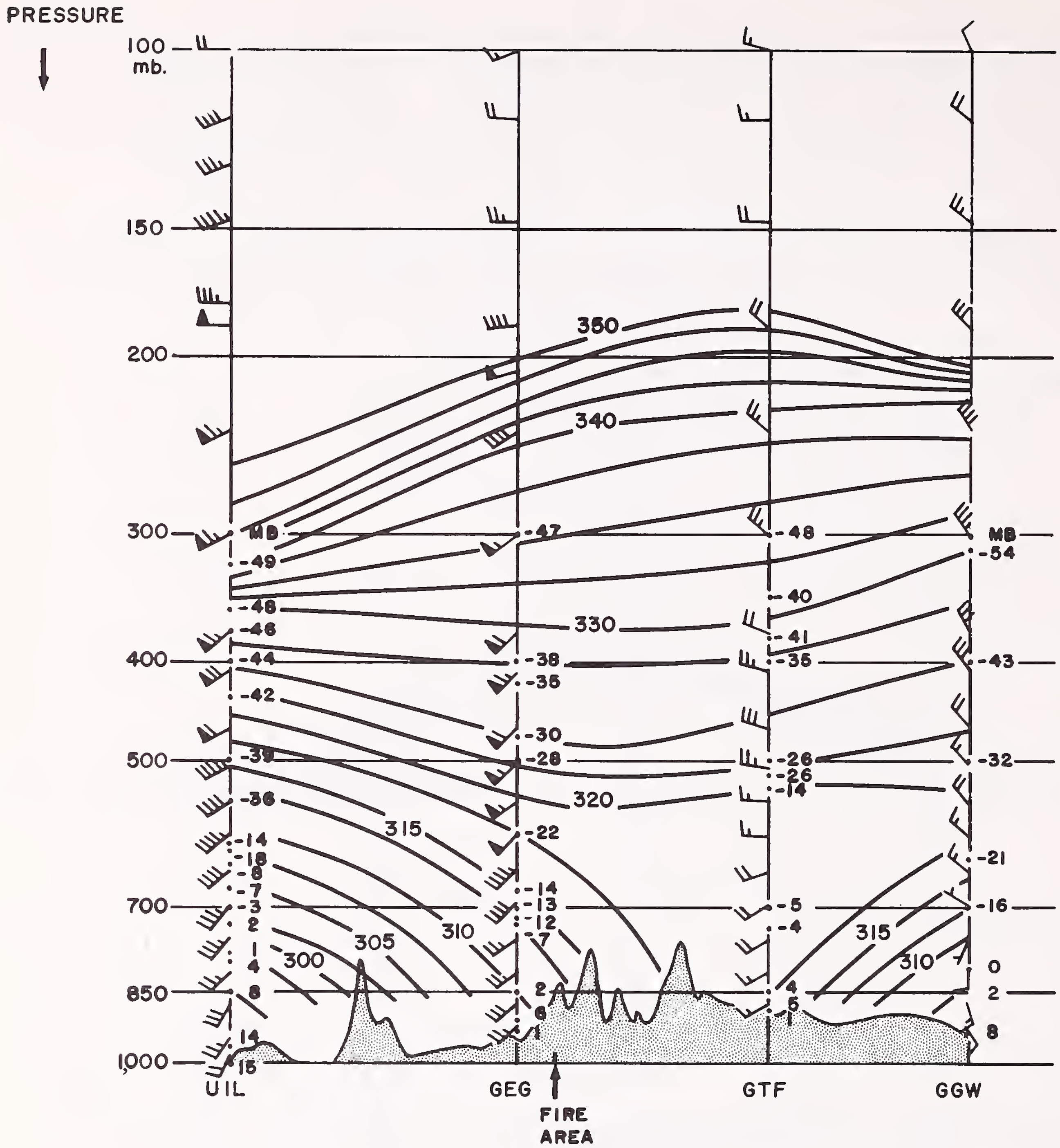


Figure 26.--Same as figure 25 for 1700 P.d.t. (m.s.t.) September 1, 1967, except dewpoint temperatures (°C.) are also plotted.

coast to eastern Montana. An additional vertical section (fig. 28) depicts the change of potential temperature over a period of time at Spokane. This time cross section (time proceeding from right to left) would also represent an instantaneous spatial (west-east) cross section if potential temperature remained unchanged as the air progressed eastward and at constant speed past Spokane. Such an assumption is, of course, an oversimplification but is still useful. The west-east orientation of these sections is approximately normal to the lower-tropospheric isotherms (figs. 5 through 7), but does not very well intersect the jetstream; to provide this latter view, north-south sections are presented in figures 29 and 30.

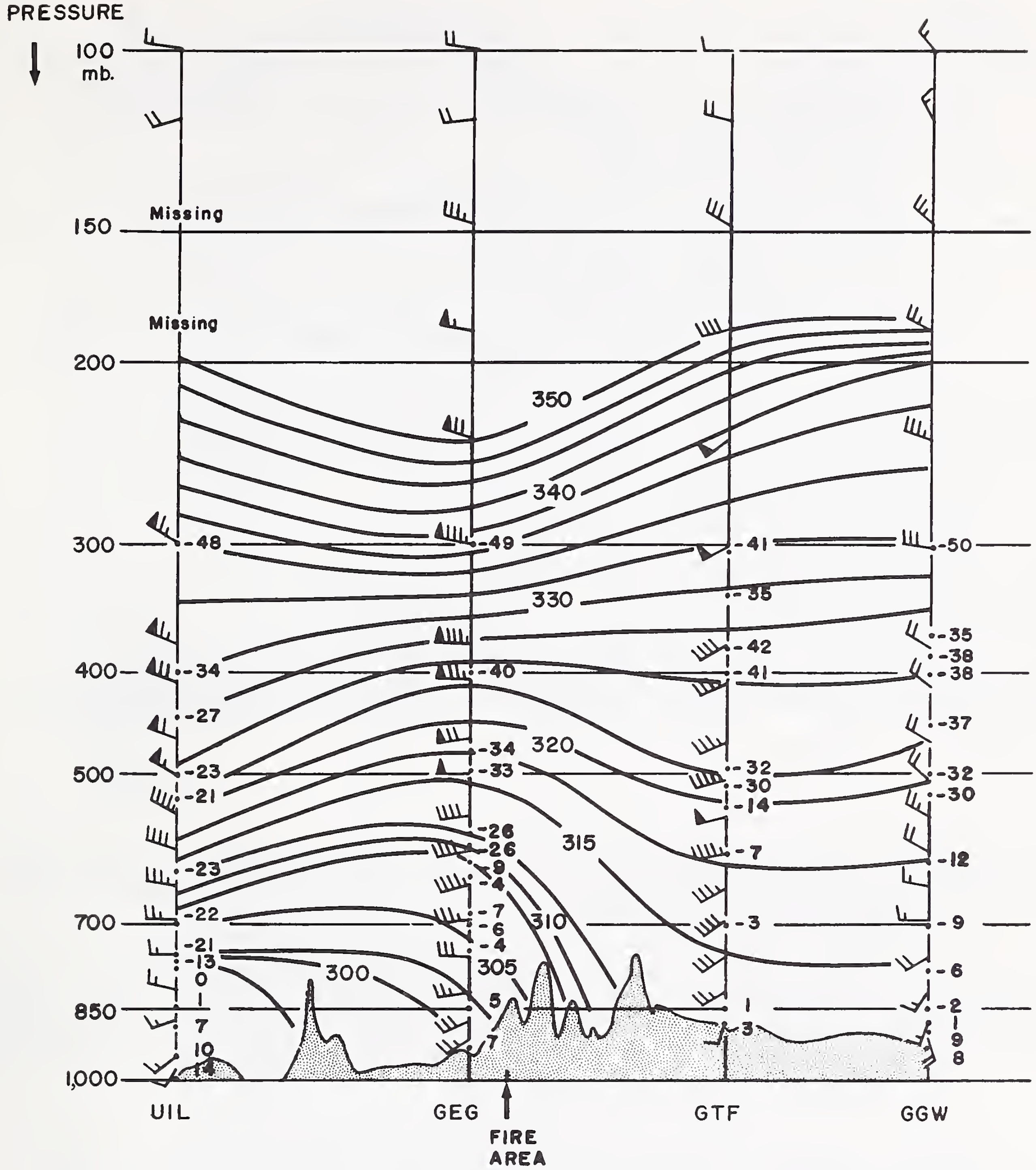


Figure 27.--Same as figure 26 for 0500 P.d.t. (m.s.t.) September 2, 1967.

The 305°-310° K. isentropes in figure 28 apparently outline (through the concentrated horizontal temperature gradient) the frontal zone in the lower troposphere, which we previously noted was west of Spokane at 1700 P.d.t. September 1. This zone was not easily discernible on the surface map as it later passed through extreme eastern Washington and the Sundance area, and it does appear somewhat diffuse here. In figures 25 through 27, which together show the eastward movement of the cooler airmass, the frontal zone at 1700 P.d.t. appears even more diffuse, but the broader baroclinic region already extends east of Spokane (in agreement with fig. 23); at 0500 P.d.t. September 2, the frontal zone was more pronounced, with its 850-mb. position now in extreme western Montana. Frontal-zone subsidence, if present, would not strictly follow the pictured isentropes which move with the weather system.

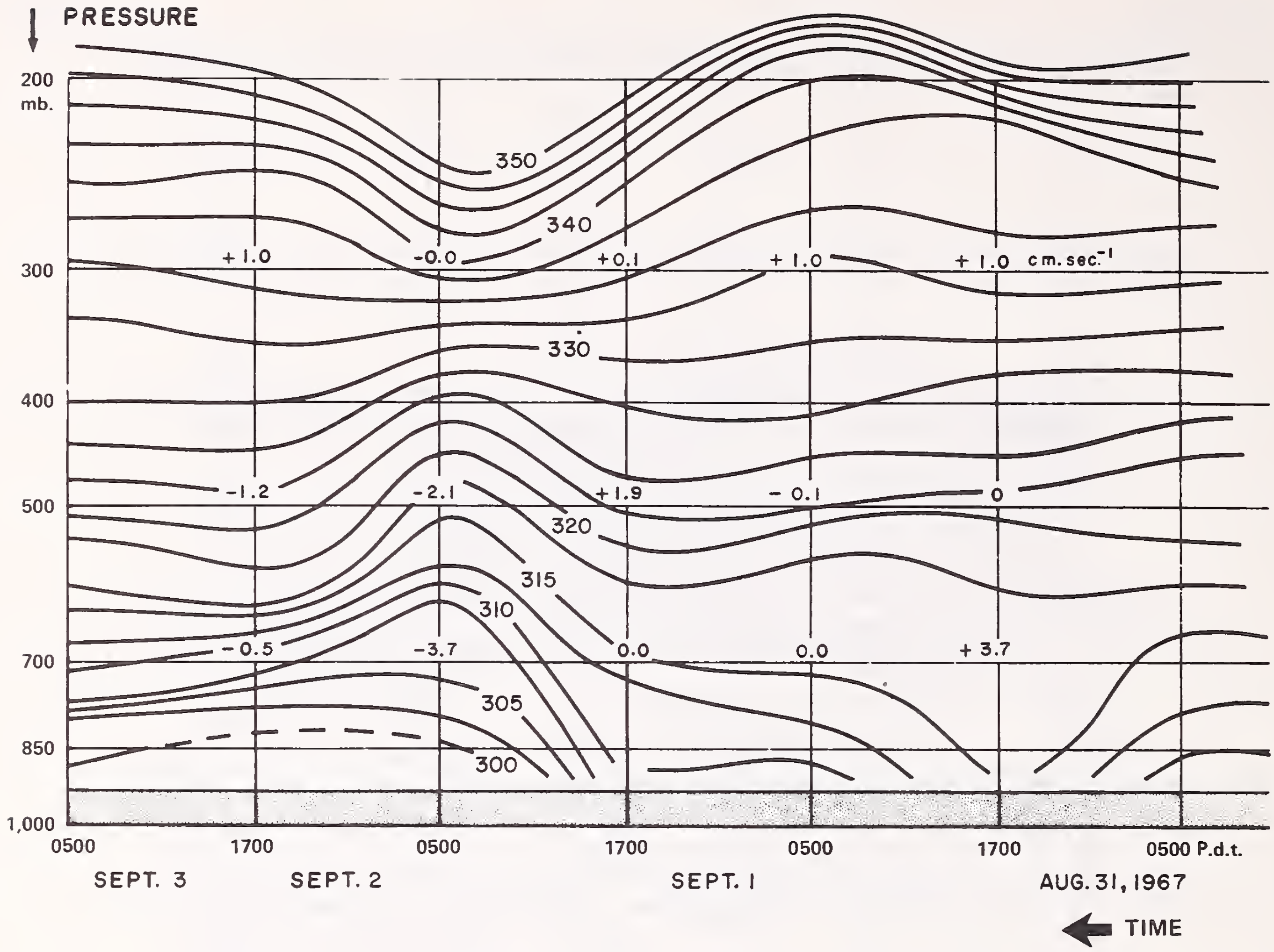


Figure 28.--Time section of analyzed potential temperature (°K.) at Spokane; isentrope interval 2.5°. Vertical component of wind (cm. sec.$^{-1}$) computed by adiabatic method is plotted at 700, 500, and 300 mb.

These cross sections suggest that such subsidence into the Sundance Fire area may have occurred during at least the later portion of the run, but originating in the midtroposphere (around 500 mb. or lower) rather than at jetstream level. This apparent limitation, however, could possibly be a fallacy related to the west-east section orientation.

Figures 29 and 30 indeed indicate that descending motion could occur (along the 315° K. isentrope) from about 350 mb. on the north side of the jet axis to below 500 mb. at Quillayute and thence to lower levels, possibly eastward to the Sundance area. Looking further, however, at maps of the 315° K. isentropic surface (figs. 31, 32, and 33), we find little supporting evidence that frontal-zone subsidence into this area on September 1 (implied by airflow from lower to higher pressure) was from north of the jet axis and thus from the upper troposphere (over the Gulf of Alaska). Such descent, fitting Reiter's (1963) model, may have possibly existed in a more roundabout way, obscured by the data void.

The vertical velocities over Spokane included in Figure 28 were computed by the "adiabatic" method (Petterssen 1956) and may be only roughly true. Plus signs denote upward motion; negative signs, downward motion. The dry-adiabatic assumption itself is generally valid for regions of synoptic-scale descending motion and also in ascending motion where saturation is not reached, as in the present case. However, nonadiabatic temperature changes, from radiational cooling or heating, likely affected the lower troposphere, particularly below 700 mb. Details of the computation are given in the Appendix.

Figures 29-30.--North-south cross section along coastal vicinity from southeastern Alaska to southern Oregon. Solid lines are isentropes, drawn at 5° K. intervals; dashed lines are isotachs, drawn at 20-knot intervals.

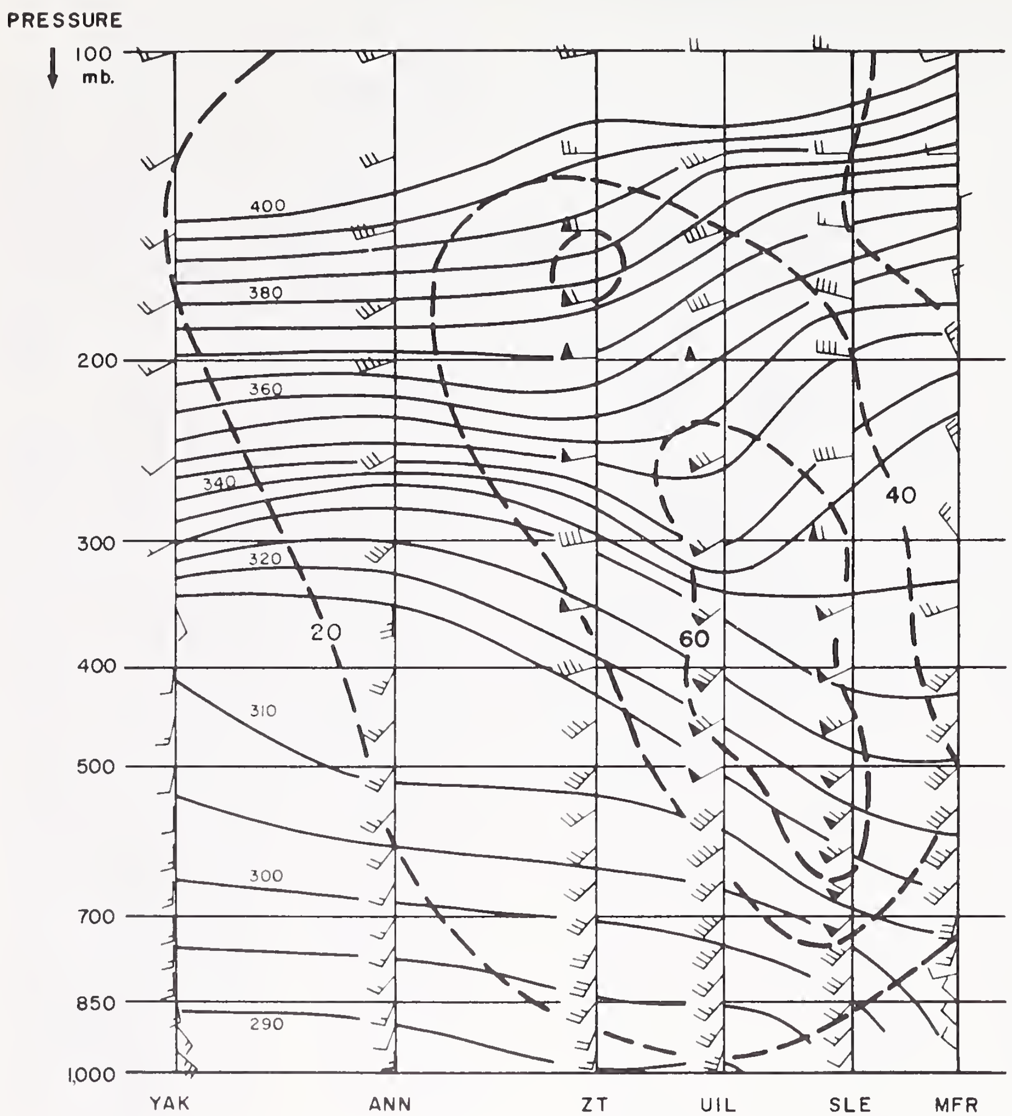


Figure 29.--1700 P.d.t., September 1, 1967.

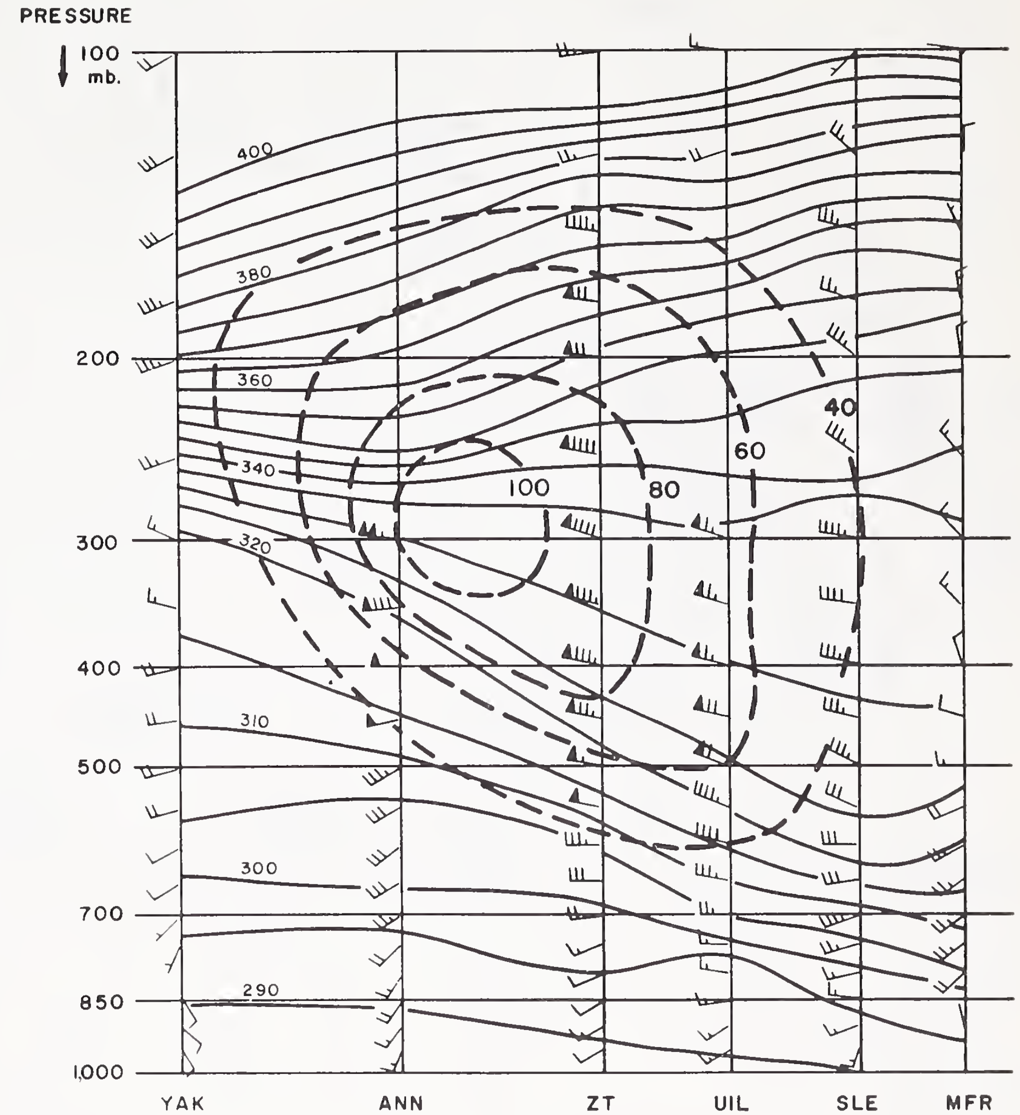
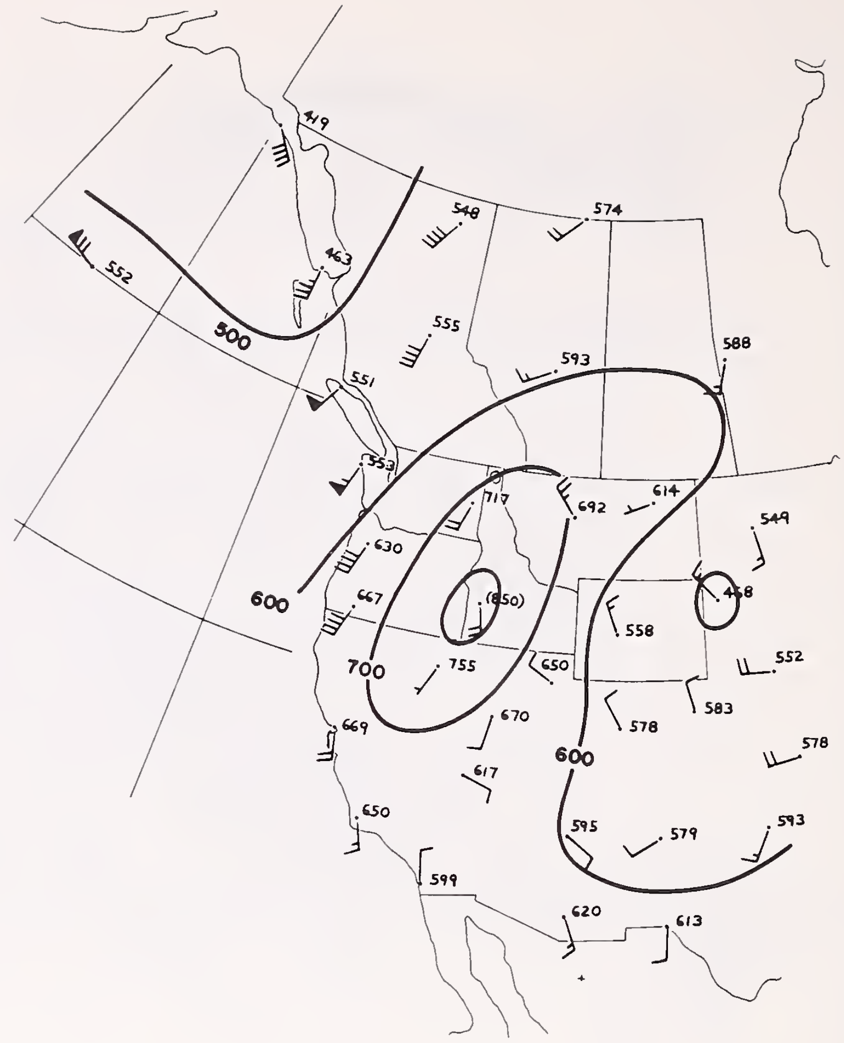


Figure 30.--0500 P.d.t. September 2, 1967.

Figure 31.--Map showing pressure (mb.) and wind (speed in knots) at 315° K. isentropic surface, 0500 P.d.t. September 1, 1967. Solid lines are isobars.



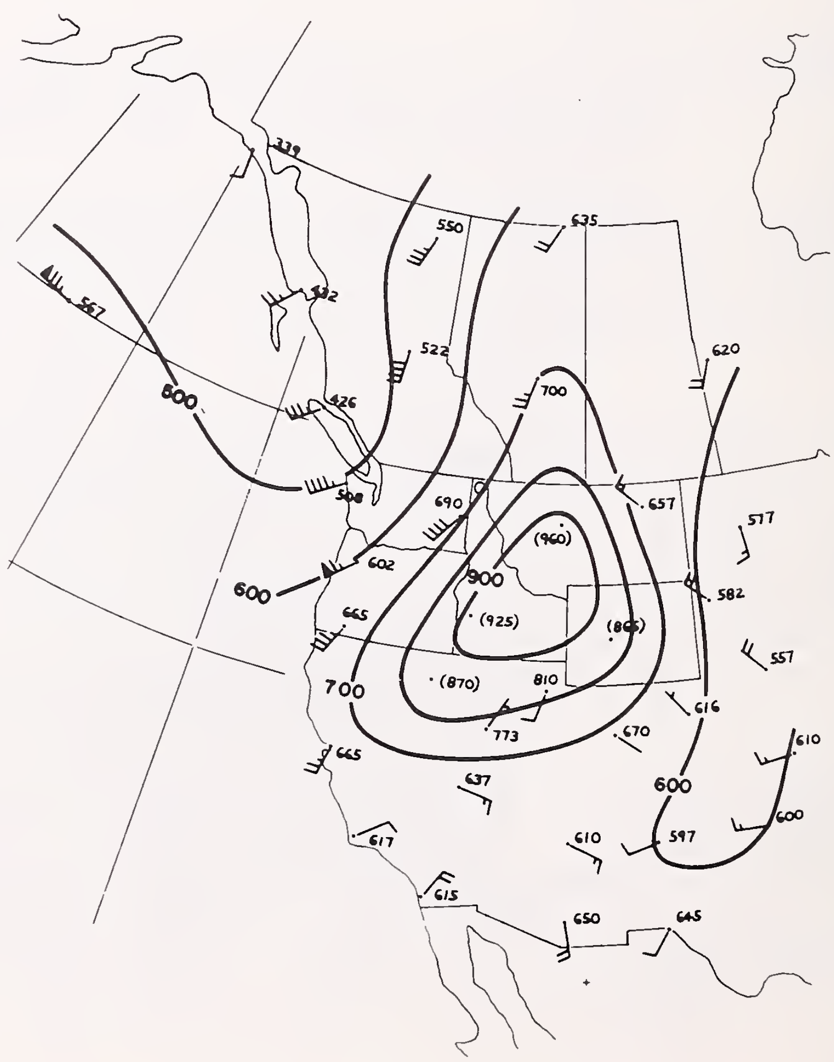
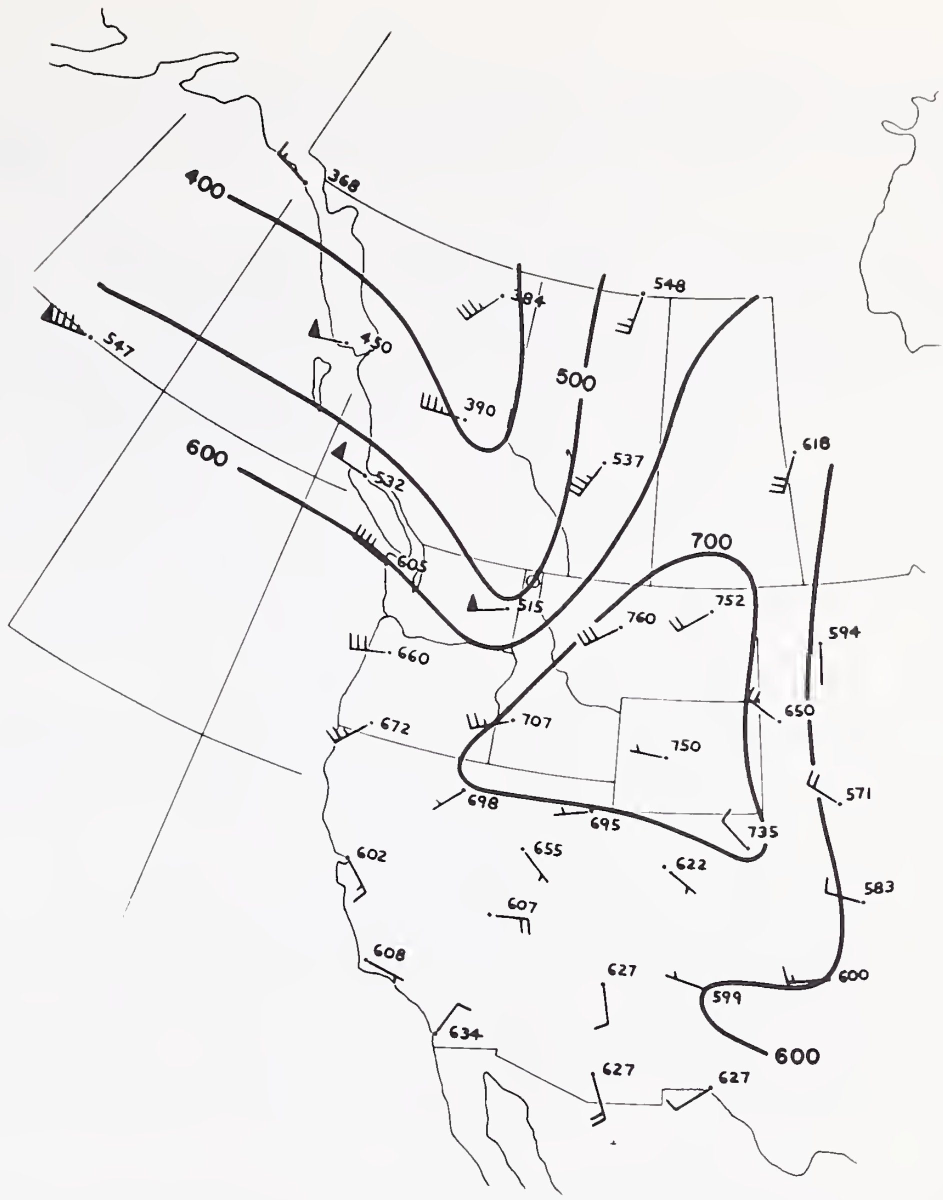


Figure 32.--Same as figure 31, but for 1700 P.d.t. September 1, 1967.

Figure 33.--Same as figure 31, but for 0500 P.d.t. September 2, 1967.



The velocity values here again suggest frontal-zone descending motion later in the fire run, but show upward motion, if any, early in the run. Some descent, however, might possibly be implied also early in the run below 700 mb., where the computed velocity at 1700 P.d.t. was 0.0 (compared with +2 cm. sec.$^{-1}$ at 500 mb.). Such change of motion sign in the vertical, within the troposphere, can occur because the adiabatic motions have considerable horizontal components; upper and lower portions of the descending air trajectory may be a day or more apart. Vertical motions on a smaller scale, e.g., within the main frontal zone, may of course be greater than those computed here. The negative velocity values indicated above midtroposphere (500 mb.) just after the fire run apparently represent larger-scale subsidence above and following the cold-air dome, rather than that occurring in a cold-frontal zone.

The above-mentioned zero vertical velocity computed at 700 mb. at 1700 P.d.t. agrees reasonably well with the isentropic-map indication for this time (fig. 32). At first glance, there is a slight downward motion over Spokane near 700 mb. (wind from lower to higher pressure); however, referring to the preceding map (fig. 31), the actual airflow trajectory reaching Spokane around 1700 P.d.t. appears to have been more southerly and thus parallel to the pressure contours.

At 500 mb., the local cooling trend that began just prior to 1700 P.d.t. (fig. 28) began with only neutral thermal advection indicated (fig. 34); the upward vertical velocity computed at this level (+2 cm. sec.$^{-1}$) thus implies that the cooling was due to adiabatic ascent. Neutral thermal advection at this time was also indicated by the Spokane winds aloft, which at 1700 P.d.t. showed no vertical change in direction around 500 mb. (between 550 and 450 mb.). Figure 35, showing the 500-mb. pattern 12 hr. later, at 0500 P.d.t. September 2, suggests that strong cool-air advection must have set in

Figures 34-35.--500-mb. maps. Solid lines are height contours, labeled in tens of meters, drawn at 60-m. intervals; dashed lines are isotherms at 5° C. intervals.

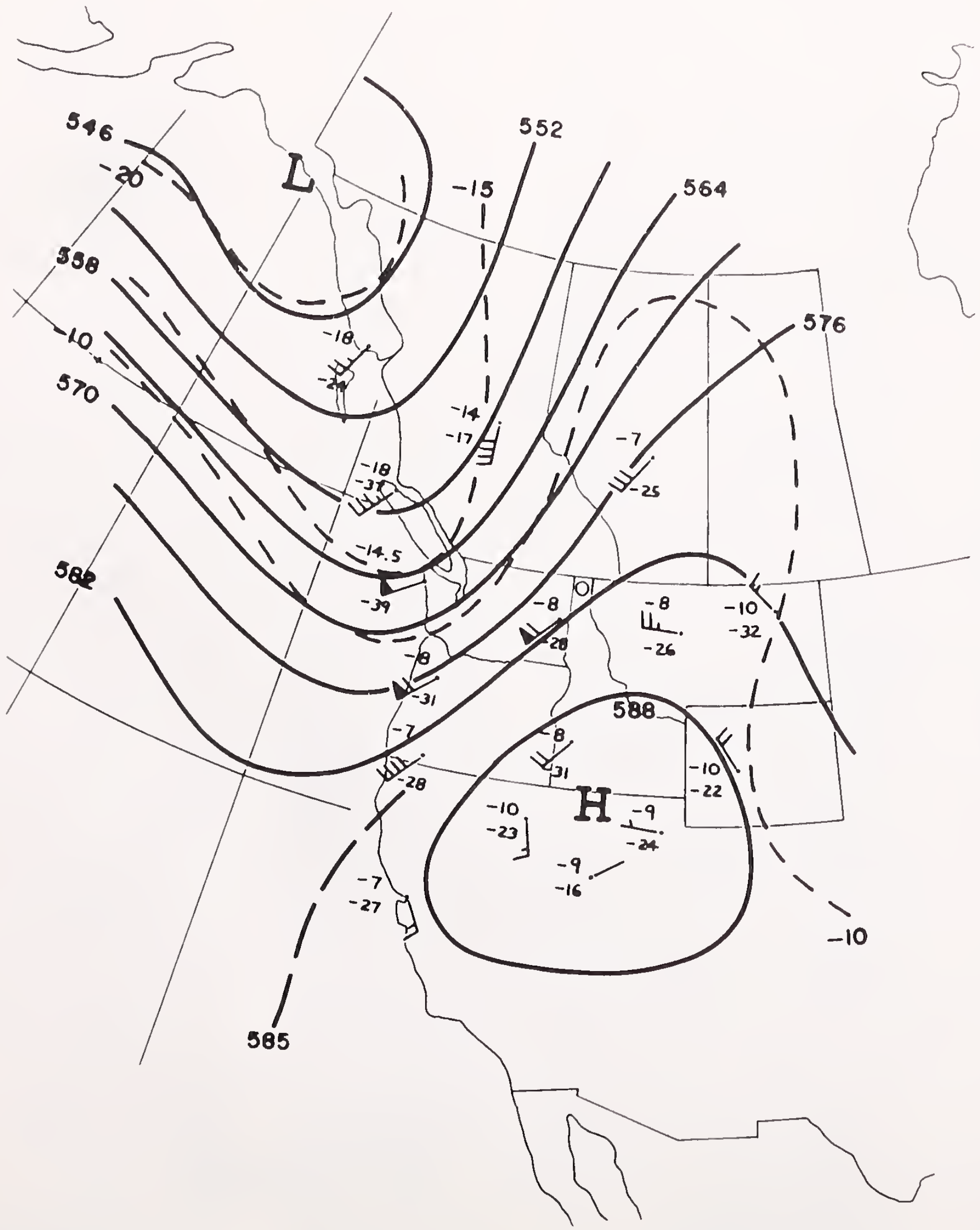


Figure 34.--1700 P.d.t., September 1, 1967.

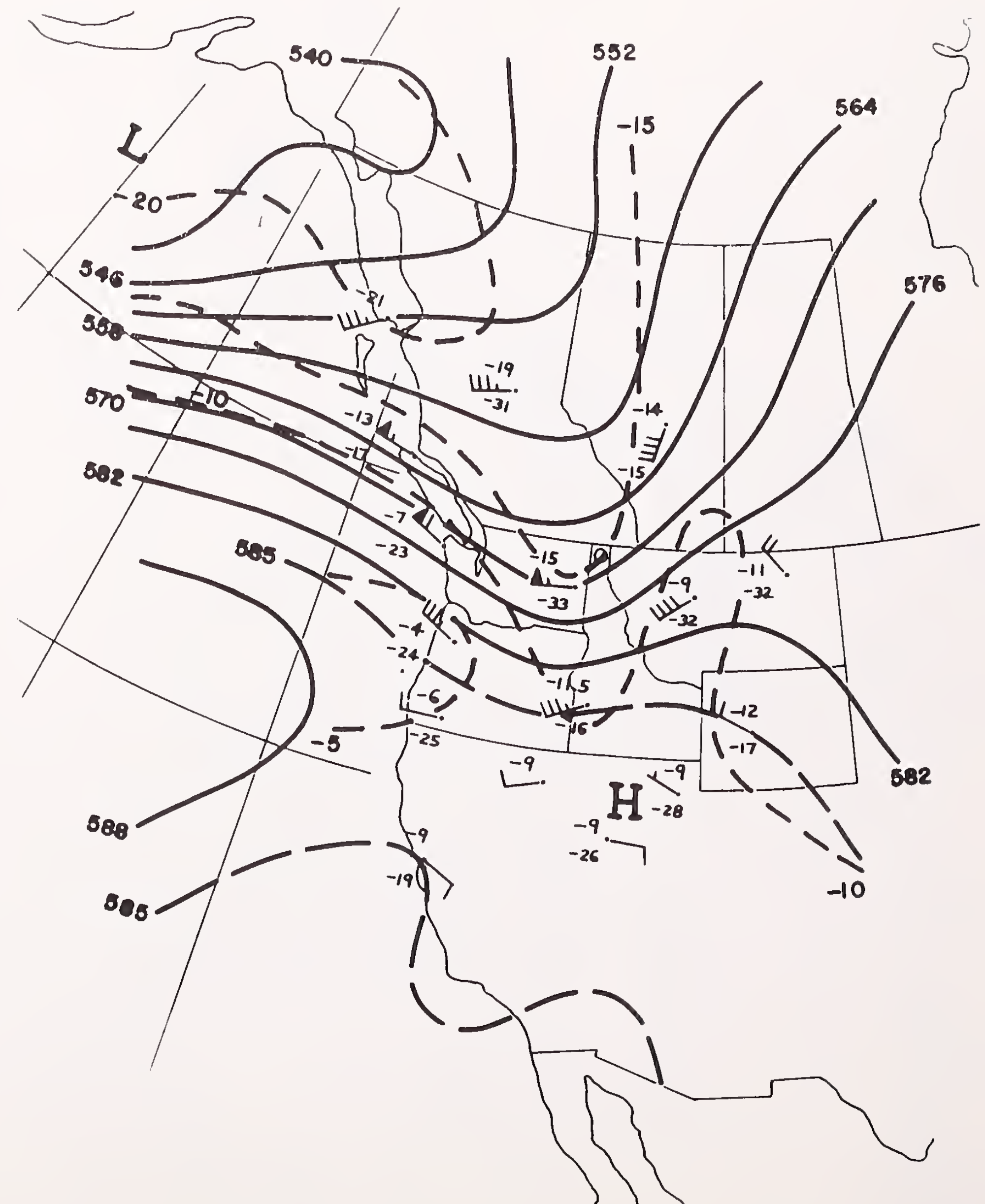


Figure 35.--0500 P.d.t., September 2, 1967.

within a few hours after 1700 P.d.t. Compensating adiabatic descent is implied in the computed 0500 P.d.t. vertical velocity (-2 cm. sec.$^{-1}$) at 500 mb.; the velocity reached -4 cm. sec.$^{-1}$ at 700 mb. Stronger descent may have occurred somewhat earlier, in the frontal zone.

As to the actual effect of subsidence during the Sundance Fire run, it appears to have been minor. Free-atmosphere relative humidity in the area was already critically low in advance of such possible motion related to the cold front. The existing dry tropospheric air may, however, have had a past history of broad-scale subsidence. The strong wind attending the run was related primarily to a steep trough-associated pressure gradient existing at all tropospheric levels.

Minimum dewpoint temperatures of 28° F. were reached on September 1 at Big Spot, Gisborne Mountain, and Lunch Peak between 1800 and 2000 P.d.t., but these were only 1° to 4° lower than on the previous day. (Also see mixing ratios in fig. 16.) They were about 10° F. higher than those found by Krumm[5 6], as typical in severe subsidence cases.

A pronounced decrease in humidity did, however, occur during this same afternoon in local areas to the east in northwestern Montana and extreme southwestern Alberta. For example, the dewpoint at Kalispell, Montana, 3,000 ft., fell from 45° F. at 1400 m.s.t. and 43° F. at 1500 m.s.t. to 14° F. at 1600 and 20° F. at 1700 m.s.t. It was rather steady, however, between 40° F. and 36° F., 100 statute miles to the south at Missoula, Montana. To the north, at Pincher Creek, Alberta, 3,800 ft., just east of the Continental Divide, the dewpoint decreased gradually from 32° F. at 1500 m.s.t. to 20° F. at 1900 m.s.t. Just west of the Divide, at Kimberley, British Columbia, 3,000 ft., it held around 35° F. At the regular 1600 m.s.t. fire-weather observation time, the dewpoint was 17° F. on Johnson Peak, Montana, 6,000 ft., about 25 miles northwest of Kalispell, but it was 31° F. at Roman Nose Lookout on the northern edge of the Sundance Fire and 42° F. at Bonners Ferry, Idaho, 1,800 ft., just northeast of the fire.

Higher-level origin of this observed drier air is evident from figure 26. With conservation of mixing ratio, the dewpoint of 14° F. (-10° C.) at Kalispell would represent air descent from at least the 700-mb. level, where the dewpoint over Spokane was -13° C. Occurring well ahead of the defined cold front (though near the leading edge of the broad baroclinic region, figures 23 and 26), this descent may have been a terrain (possibly lee-wave) effect found in the lee of a mountain range, occurring without front-related subsidence.

Trough Movement in Relation to the General Circulation

As previously noted, an approaching upper trough was an important contributing factor to the strong gradient wind that reached the Sundance Fire area. Resumption of this trough's eastward movement on August 31, after being stationary for 3 days between 145° and 150° W., coincided with an increase in the midlatitude Pacific area "zonal index" (fig. 36). In the change from relatively low-index conditions of August 27 through 30, the band of maximum westerlies shifted about 7° of latitude northward by September 2. This pattern of change corresponds roughly with the cycle of northward drift of relative maximum (maximum for a particular latitude) described by Riehl and others (1952), but these cycles behave neither regularly nor predictably.

Figure 37 indicates that very little readjustment in mean longitudinal position of the eastern Pacific trough followed this increase in zonal index. Instead, the original offshore trough apparently became a short wave after moving inland, while a

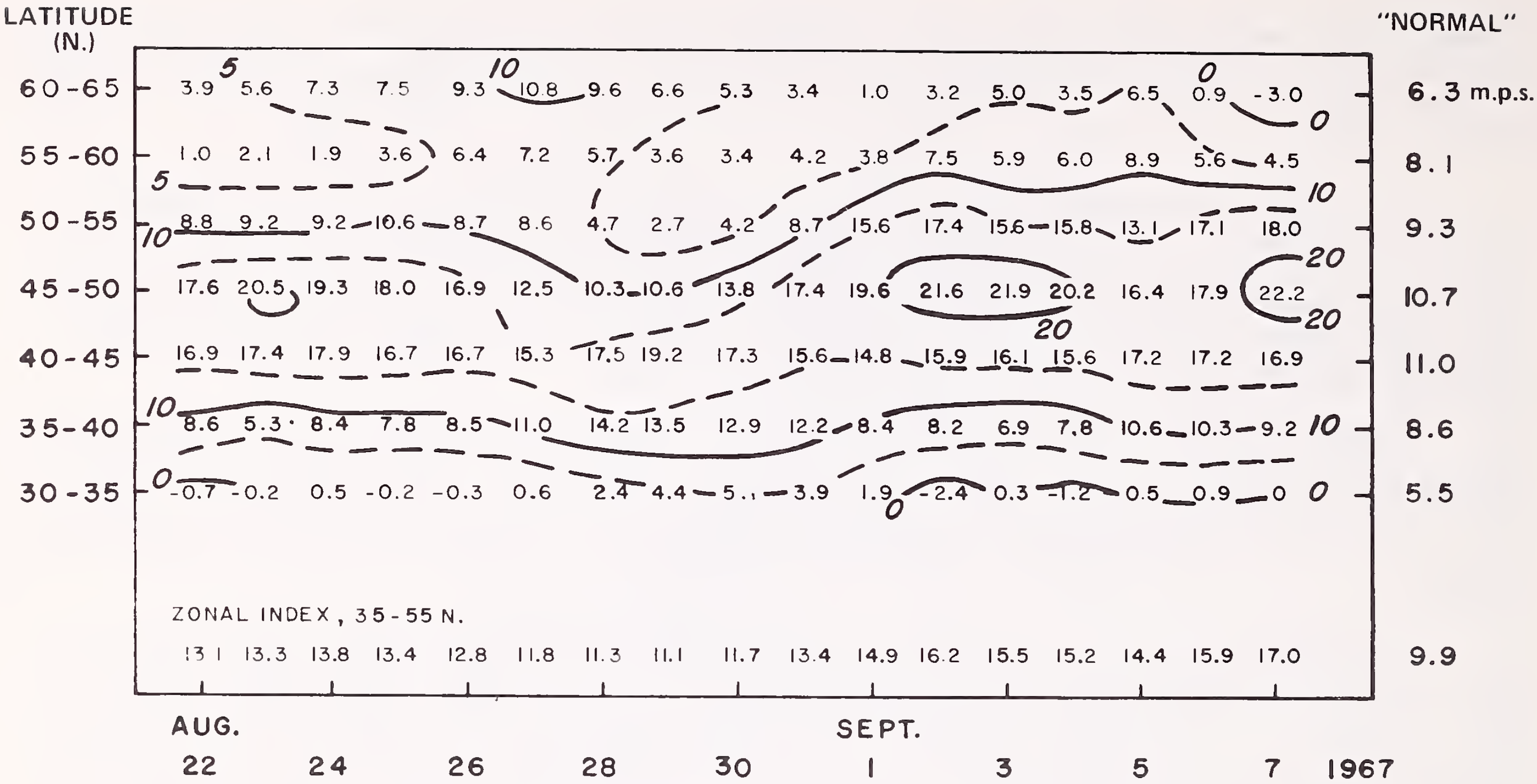


Figure 36.--Geostrophic westerly wind components at 500 mb., in m.p.s., averaged across Pacific Ocean area, longitude 120° E. through longitude 100° W., by 5° latitude bands, August 22 through September 7, 1967 (0000 G.M.T. observations); computed from daily 500-mb. maps machine-analyzed by National Weather Service NMC. "Normal" components computed from normal 2-week mean (August 23 through September 7) height contours at 500-mb. (National Weather Service Extended Forecast Division) are listed on right side.

succeeding trough, which had moved rapidly across the northern Pacific, subsequently became established in the same long-wave position (under the downstream effect of a blocking ridge over the Bering Sea area). A strong, warm ridge redeveloped over the Western United States but slightly more eastward than previously. As a result, abnormally warm and dry weather returned to the Northern Rocky Mountain area, accompanied by some thunderstorm activity, and the fire season continued throughout much of September 1967.

With the entire 1967 fire season in mind, it is of interest to note that some researchers (e.g., Namias 1968) have related the persistence of an offshore upper trough position to a possible "feedback" effect. Such a persistent trough during the 1967 season probably helped maintain (for example, from the viewpoint of constant absolute vorticity trajectories) the persistent ridge aloft that parched the Pacific Northwest-Northern Rockies area. The "feedback" effect involves the ocean and its relatively slow warming or cooling. In this case, there are abnormally warm sea-surface temperatures in advance of the trough, related to anomalous southerly airflow, and abnormally cool sea-surface temperatures west of the trough. The increased longitudinal temperature gradient of the water, in turn imparted to the atmosphere, is said to favor increased baroclinic development of cyclones coming within the region of the trough, thus tending to maintain its mean position. The trough's location could, of course, be influenced also by neighboring features of the general circulation. Clark (1967), in fact, found that during a 7-year period monthly anomalies of North Pacific sea-surface temperatures were not any more persistent than those of air temperatures and he thus questioned the importance of ocean "feedback" as a general-circulation control.

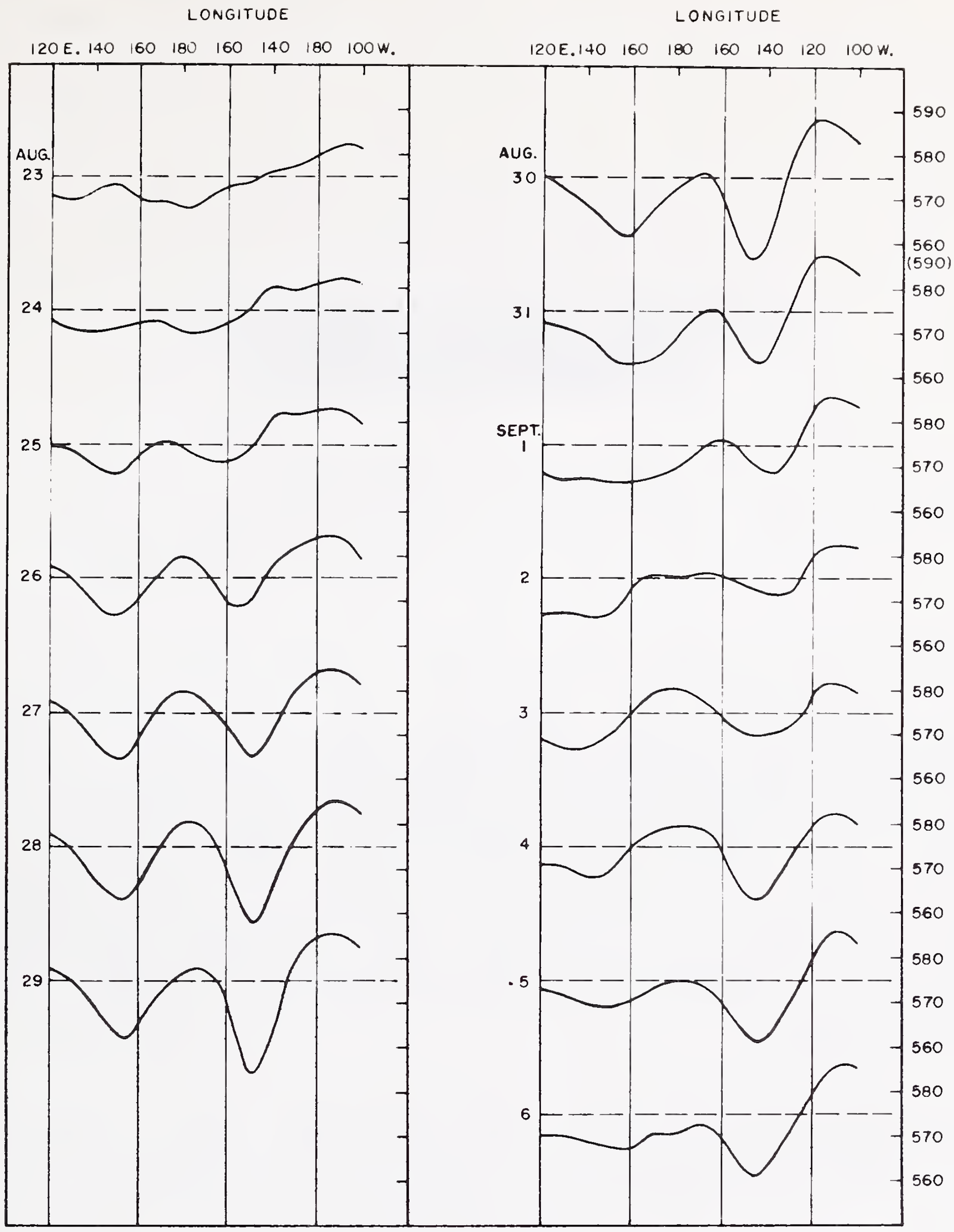


Figure 37.--500-mb. height profile (in tens of meters) across Pacific Ocean area, longitude 120° E. through longitude 100° W., averaged through 20° latitude band (using heights at 35°, 40°, 45°, 50°, and 55° N.). Heights are 3-day averages plotted at middle date, based on 0000 G.M.T. maps machine-analyzed by National Weather Service NMC. Solid horizontal lines represent height of 5,750 m.

Whatever their significance may be, warmer than normal sea-surface temperatures certainly prevailed off the North American west coast during July through September 1967 (U.S. Bureau of Commercial Fisheries 1967a, b, and c). A large area having monthly mean departures of +3° to +4° F. extended off the United States to about longitude 140° W. during August and to about 135° W. during September. Farther west, in waters centered around 150° W., temperatures averaged from near normal to about 2° F. below normal. An area around 175° to 180° W. that had departures up to +6° F. corresponds with the longitude of the mid-Pacific ridge in figure 37; this would indicate that the circulation "teleconnections" (Namias 1968) originated beyond the eastern Pacific trough.

Further discussion of the general circulation features during the memorable summer of 1967 is available in the Monthly Weather Review (Dickson 1967; Posey 1967; Wagner 1967).

CONCLUSIONS

Sustained strong southwesterly wind, the major weather factor in the Sundance Fire run in extreme northern Idaho, September 1, 1967, was primarily related to a strong pressure gradient existing at all levels of the troposphere. At 700 mb. and higher, this gradient existed between an approaching deep (though flattening) trough and a persisting warm ridge over the Rocky Mountain area. This trough began advancing early on August 31 after having been stationary for 3 days in the eastern Pacific at between 145° and 150° W. The strong wind, reaching 40 to 45 knots at as low as 5,000 ft. m.s.l. in the free atmosphere, was thus a large-scale weather-map feature, whose progress could be followed into the Sundance area. Apparently, such sustained low-tropospheric speeds ($\geq$40 knots at 5,000 ft.) in this area can (from 11 years of Spokane wind soundings) be expected on an average of no more than 2 days in the June 15 through September 15 fire season.

A dry cold front (which formed a few hours earlier east of the Cascades, replacing a dissipating Pacific front to the west) was approaching ahead of the trough aloft. Front-related turbulence may have helped trigger the strong, gusty wind conditions observed at the surface (by effecting a downward transfer of momentum through the friction layer). However, only a diffuse frontal-zone passage could be discerned across extreme northern Idaho on the surface weather map. It is likely that terrain-induced turbulence, increasing with gradient windspeed, also had a role, perhaps the main one. The synoptic-scale airmass was not unstable, but a low-level "jet" in the vertical wind profile (observed at Spokane) may have contributed to the extreme, "three-dimensional" fire behavior.

The requisite low relative humidity which existed during the fire run had persisted for 3 previous days and nights (remaining below 35 percent at ridge elevations). Large-scale subsidence was not found to enter into the immediate picture, though frontal-zone subsidence was indicated during at least the later portion of the fire run, apparently originating only from the midtroposphere. The effect of this subsidence on the surface humidity and windspeed in the fire area appeared minor.

An increase in relative humidity to above critical values late in the fire run, resulting from the advection of a cooler and moister Pacific airmass, helped (together with fuel and topographic factors) in the run's termination. The wind, at least in the free atmosphere, continued strong, though decreasing, for some hours afterward.

The Sundance Fire run was a culmination of an exceptionally warm, dry summer in the northwestern United States, which led to record fire-danger buildup. The final stroke was provided by unusually strong summertime winds coming at a most unfortunate time.

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APPENDIX

(A) Surface Weather Maps (Figs. 38 Through 43)

Figures 38 through 43.--Six-hourly surface weather maps for northwestern United States and western Canada area, 0500 m.s.t. September 1 through 1100 m.s.t. September 2, 1967. Plotted station reports follow standard model. Isobars are drawn at 3-mb. intervals and fronts are indicated in conventional symbolic form.

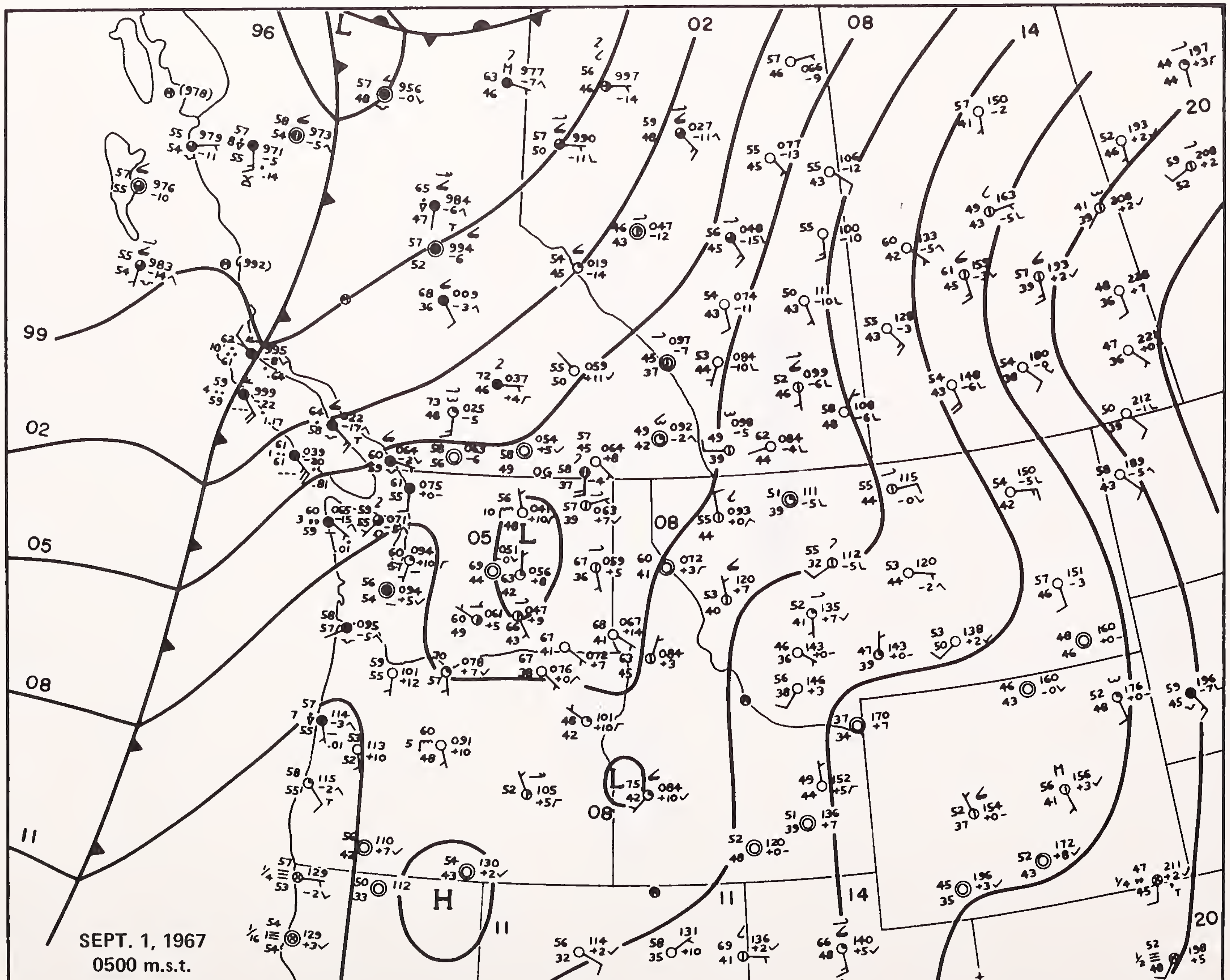

Figure 38

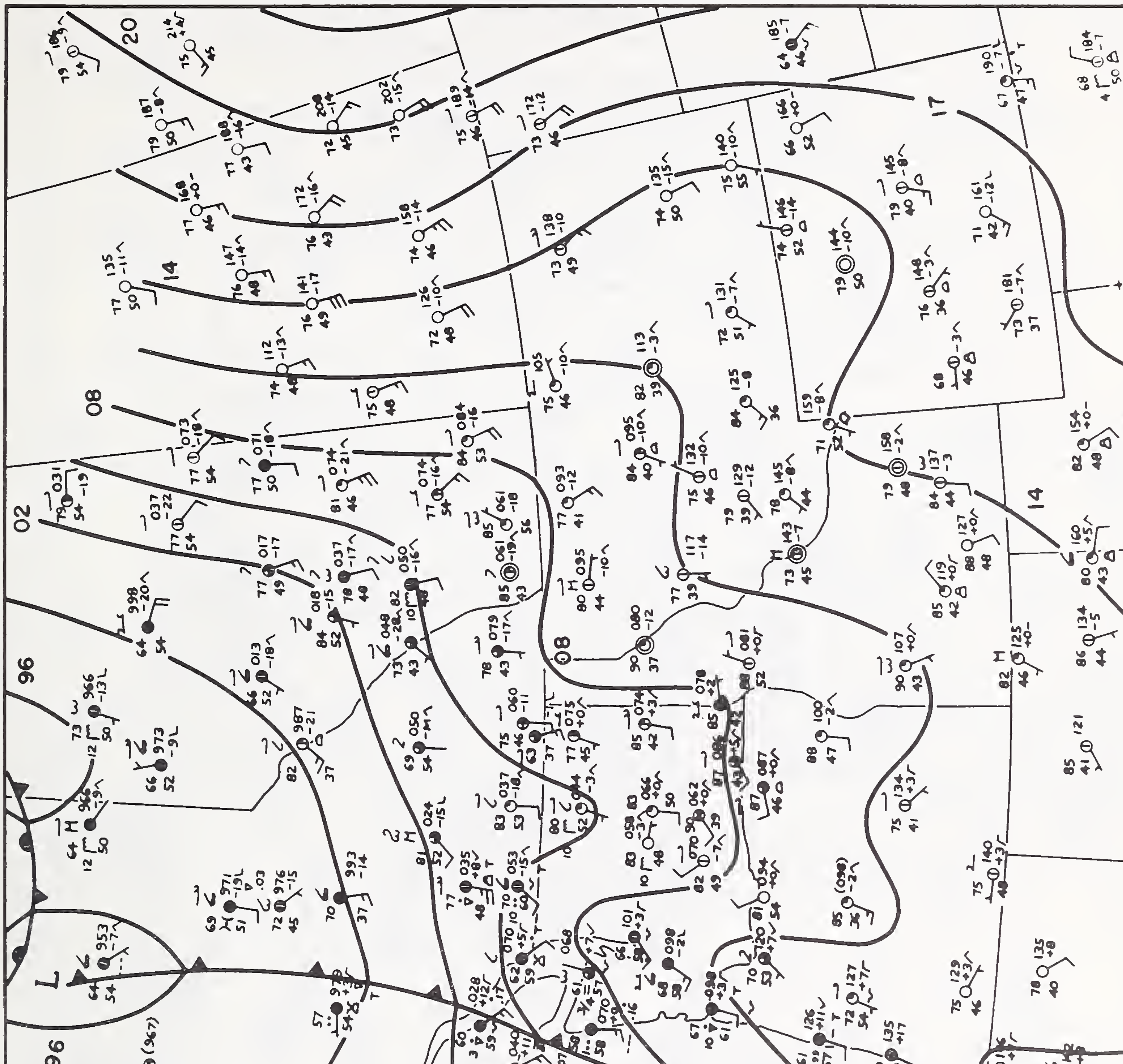

Figure 39

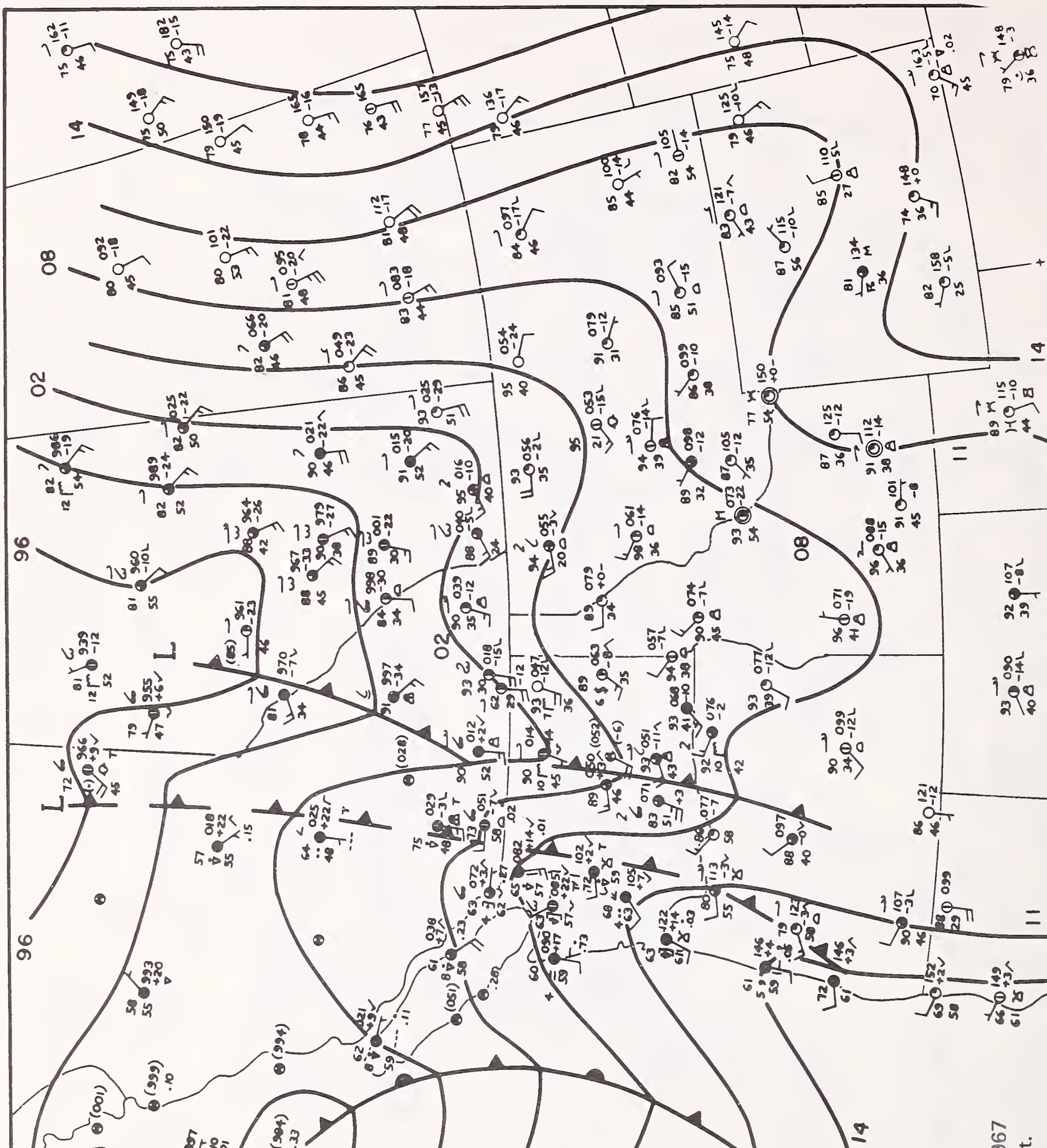

Figure 40

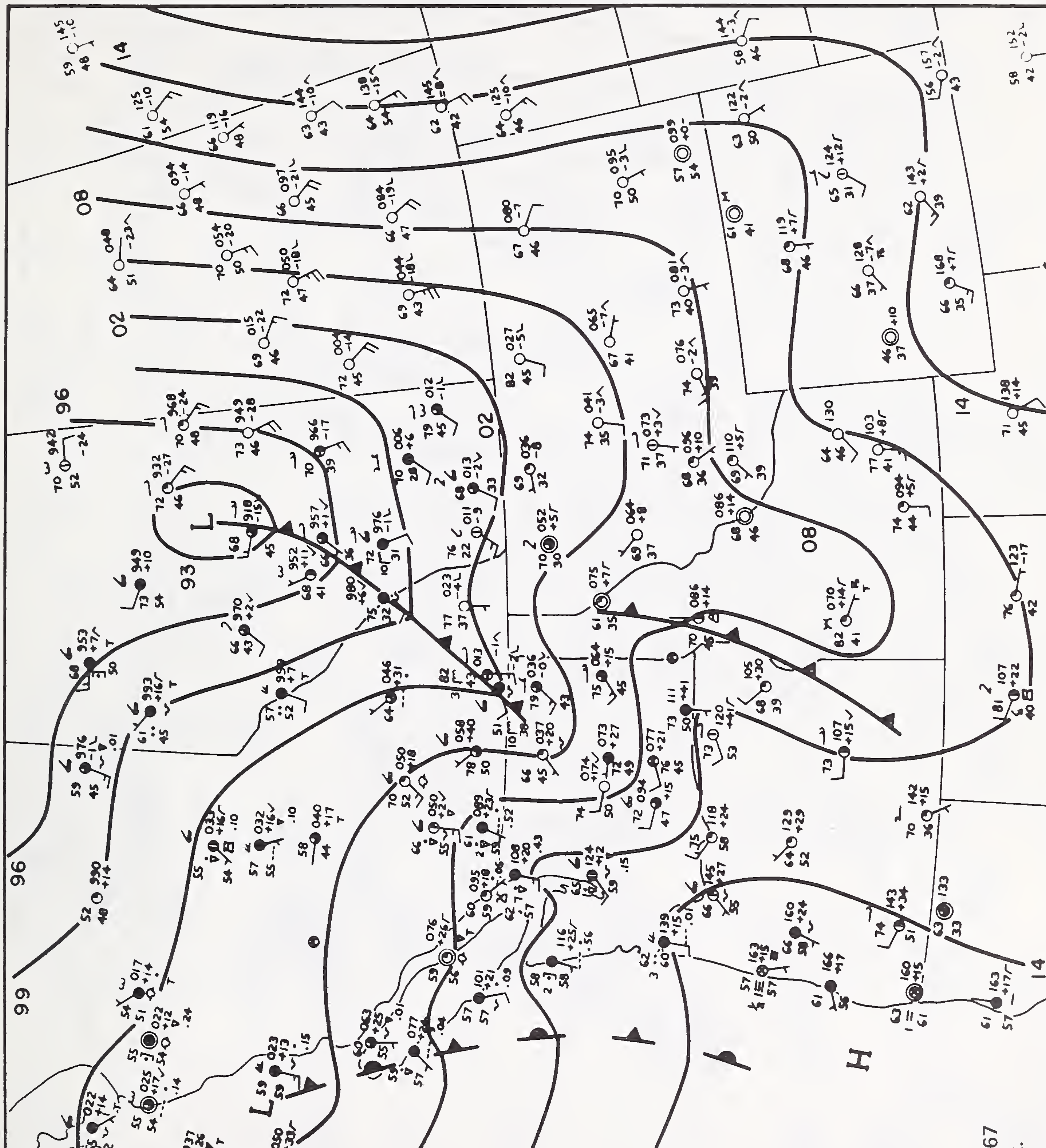

Figure 41

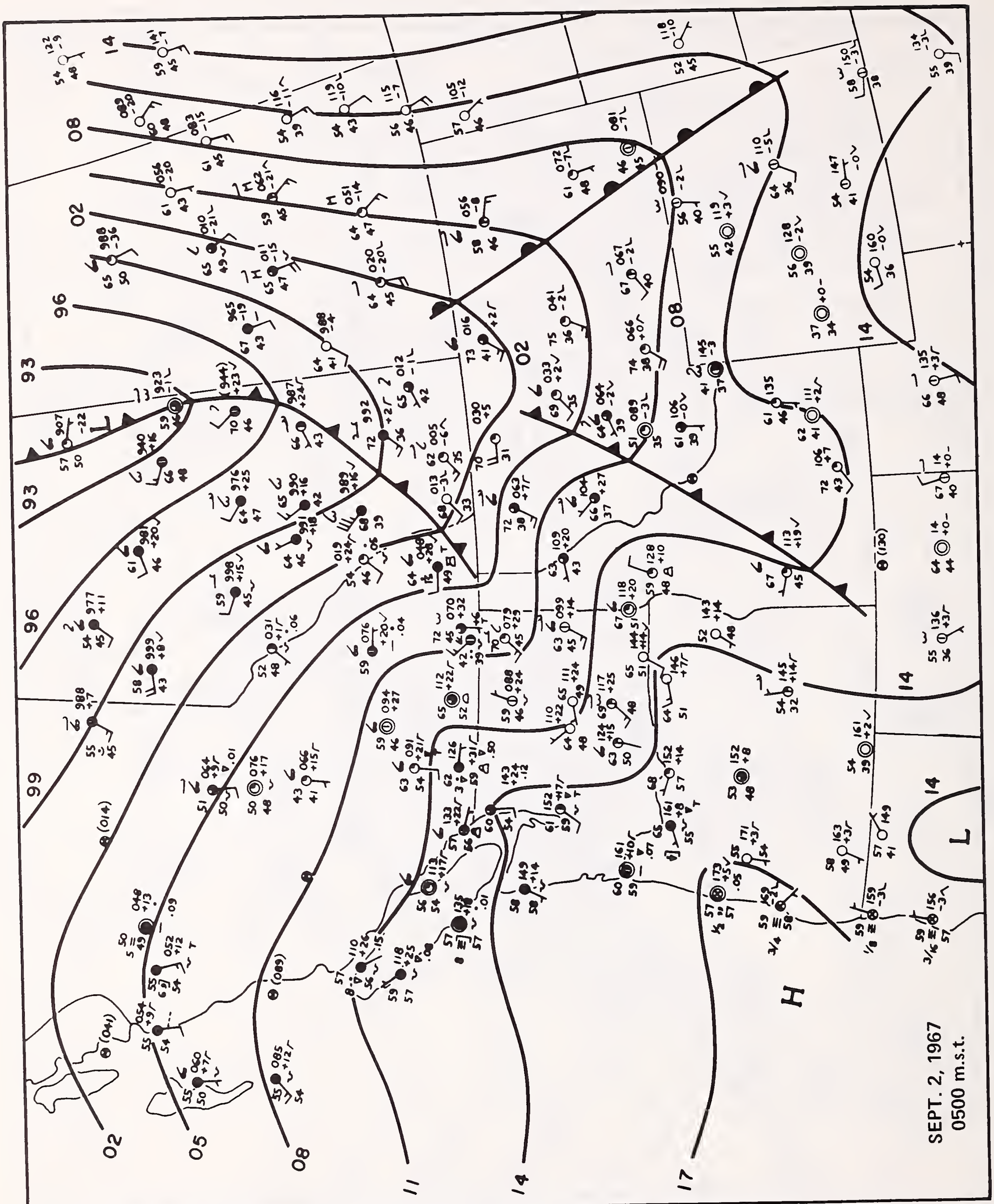

Figure 42

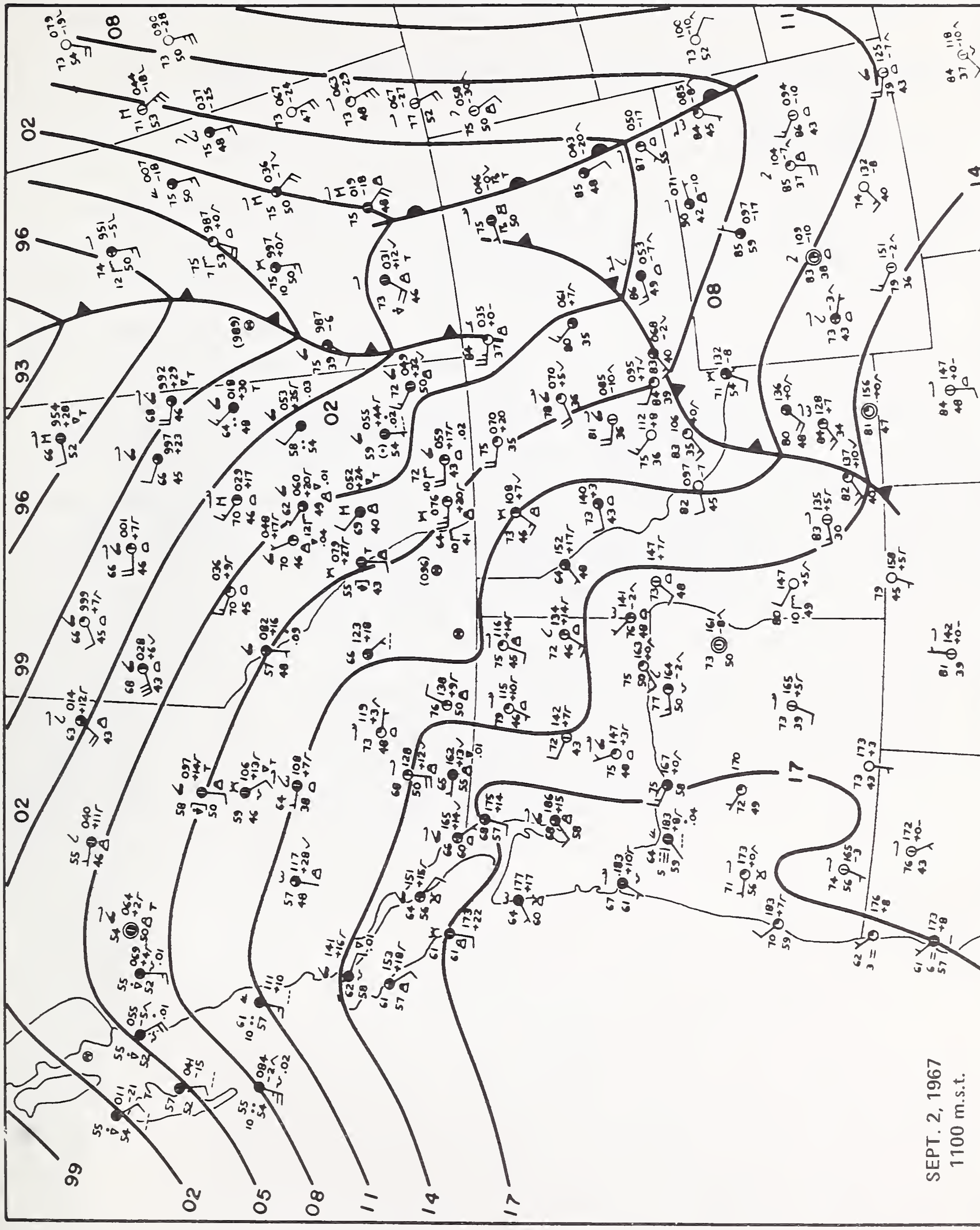

Figure 43

(B) Computation of Vertical Velocity, Adiabatic Method

Finite differences were applied to the formula (Petterssen 1956),

$$w = - \frac{\left(\frac{\partial T}{\partial t} + V \frac{\partial T}{\partial s}\right)}{\gamma_d - \gamma},$$

where w is the vertical velocity in m.p.s. (meters per second), $\frac{\partial T}{\partial t}$ is the local (observed) temperature change, and $V \frac{\partial T}{\partial s}$ the advective temperature change (negative for warm advection); V is the windspeed and $\frac{\partial T}{\partial s}$ the temperature gradient along the streamline. γ_d is the dry-adiabatic lapse rate, equal to 1.0° K. per 100 geopotential meters (gpm.), and γ the observed lapse rate, equal to $- \frac{\partial T}{\partial z}$, where z is the height increment in gpm.

The local temperature change was obtained from the time-section analysis in figure 28 (with potential temperature converted to actual temperature); Δt was 6 hr. centered at the synoptic time (3 hr. when the change was nonlinear). The advection term was taken from the appropriate constant-pressure map, with Δs generally 2 degrees of latitude, or 220×10^3 m., centered at Spokane. The observed lapse rate was obtained from a tephigram plot of temperature, using the net difference from 330 to 270 mb. for the 300-mb. value; 550 to 450 mb. for 500 mb.; and 750 to 650 mb. for 700 mb. The pressure increment was then converted to Δz.

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